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Volume 17 DECEMBER, 1928 Number 6

INTENSITY RELATIONS IN THE SPECTRA OF TITANIUM

I. Line Intensities in the Stronger Multiplets of Ti I and Ti II

By George R. Harrison

ABSTRACT

The relative intensities of the lines in 26 of the stronger multiplets of the spectrum of normal titanium, Ti I, and in 8 of the stronger multiplets due to the singly ionized atom, Ti II, were measured by a general method of photographic photometry which is described in detail. In Ti I, 58% of the multiplets were found to obey the intensity formulas to well within 5%, while in the 42% of abnormal multiplets, 71% of the lines were found normal, with 16% abnormally weak and 13% abnormally strong. In Ti II, 62% of the multiplets measured were normal, while of the abnormal 38%, 61% of the lines were normal, with 21% abnormally weak and 18% abnormally strong. Of all the lines measured, 86% appeared normal in intensity, while 7.6% were too weak and 6.4% were too strong. The departures from the predicted intensities are often fairly large, generally being of the order of 10% to 40%. No definite correlation was found between intensity abnormalities and depatures from Lande's interval rule or the normal Zeeman patterns.

The writer has for some time been engaged in making measurements on the relative intensities of lines and multiplets in the spectra of normal and singly ionized titanium, Ti I and Ti II. Titanium was chosen as having the most completely worked out spectra of any of those which are typical of the general degree of complexity of spectrum of most elements of the first long period. All term assignments, electron configurations, etc., used are taken from the recent work of H. N. Russell[1] on the titanium spectra, and the writer wishes to record his great indebtedness to Professor Russell, not only for generously furnishing much of this material in advance of publication, but for giving him the benefit of several illuminating discussions of the subject.

The principal sections of the general problem now under attack are the following: (1) The relative intensities of lines in multiplets; (2) the relative intensities of multiplets in triads, pentads, and super-multiplets,

[1] H. N. Russell, Astrophysical Journal, *66*, pp. 283–328, 347–438; 1927.

(3) the relative intensities of triads belonging to the same electron jump, ( ) the relative total intensities emitted from different electron jumps. The present paper deals with the photometric methods used and gives results for the relative intensities of lines in a number of the stronger multiplets in the quintet and triplet systems of Ti I, and in the quartet system of Ti II.

With the recent rapid development of accurate quantitative methods of photographic photometry[2] many of the chief difficulties involved in line intensity determinations have been removed. There remain, however, several intermediate steps which often stand between the actual measure of the relative strengths of two or more lines and their correlation with theoretical values. These are self-reversal, non-negligible frequency differences between lines, and departure of excitation conditions from simple statistical equilibrium at a known temperature.

While only a small amount of experimental work has been done on line intensities in complex spectra, it is sufficient to show that the theoretical formulas[3] generally hold to within at least five per cent but that in many cases individual lines show wide deviations from the rules, and often from the fundamental sum rule.[4] Frerichs[5] has measured the relative intensities of lines in 29 multiplets belonging to various elements of the iron group, and has discovered numerous exceptions to the intensity rules. He found no correlation between departure from these rules and from Lande's interval rule. He, as had van Milaan,[6] showed the necessity of reducing self-reversal to a minimum by using an arc at low pressure and with small current as a source of light.

In many cases, as in stellar and furnace spectra, self-reversal cannot be controlled in this manner. It seemed desirable therefore to study its effect on line intensities under different conditions, with a view to determining a possible method of correction which could be applied when its elimination was impossible or undesirable. Such a method is discussed in the present paper.

[2] For outlines of methods, and bibliography, see
L. S. Ornstein, Proc. Phys. Soc. London, *37*, p. 334; 1925.
H. B. Dorgelo, Phys. ZS., *26*, p. 756; 1925.
G. M. B. Dobson, I. O. Griffith and D. N. Harrison: Photographic Photometry, Clarendon Press, 1926.

[3] R. de L. Kronig, ZS. f. Phys., *31*, p. 885; *33*, p. 261; 1925.
Sommerfeld and Hönl, Sitz. Preuss. Akad. Wiss., *9*, p. 141; 1925.
H. N. Russell, Proc. Nat. Acad. Sci., *11*, pp. 314, 322; 1925.

[4] H. C. Burger and H. B. Dorgelo, ZS. f. Phys., *23*, p. 258; 1924.

[5] R. Frerichs, Ann. der Phys., *81*, p. 807; 1926.

[6] J. B. van Milaan, ZS. f. Phys., *34*, p. 921; 1925; *38*, p. 427; 1926.

PHOTOMETRIC ARRANGEMENTS

This work was begun with a 12 ft. grating, but it was soon found that a higher dispersion was desirable, both to cut down the intensity of the background relative to that of the lines, and to separate close lines in these very complex spectra. A change was then made to a 21 ft. grating, but while this proved satisfactory for many multiplets, most work reported on here was done in the second order of a 10 m concave grating with 5900 lines per cm. This very excellent grating was ruled by Wood at Johns Hopkins. It contains about 85,000 lines, and the dispersion in the second order, with the set-up used, varies between 0.7 and 0.8 Angstrom per mm. With an ordinary metallic arc in air 3 sec. exposure suffices in the first order, and 10 sec. in the second. With the low pressure arc, no exposure over one minute in length was necessary. Most of the results reported on here were obtained with an exposure time of 50 sec.

The short time required for exposure was a very great advantage, as high accuracy in photographic photometry depends on the collection of a large amount of data. Each plate taken involved the making of 38 fifty-second exposures, which could readily be done in several hours, with a resulting constancy of experimental conditions.

Both the 10 m and 21 ft. gratings have been installed in a manner especially suitable for intensity measurements. A modified Paschen type mounting was chosen, with fixed slit and grating, and a long curved track in the focal plane. Ten cassettes are provided which slide on the track of either grating mounting and can be clamped at any wave length desired between 2000 Angstroms in the first order and 4500 Angstroms in the third order. No focusing adjustments are required, the only change necessary when shifting from one spectral region to another being to place the pointers of the cassettes opposite the desired wave lengths on the scale. Each cassette contains an adapter, this being merely a frame which moves in vertical ways in the cassette, and which contains horizontal ways in which the plate holder can move through a distance of 4 cm, this being provided for convenience in calibration of plates. The plate holders are built to take 4×10 in. plates. All cassettes, adapters, and plate holders are interchangeable and can be used on either grating, or on a 12 ft. plane grating, or on glass or quartz spectrographs used for experiments on photographic plate characteristics.

The horizontal slot in the front of each cassette gives a spectrum 225 mm long with lines about 4.8 mm long, thus covering a range of about 180 Angstroms in the second order of the 10 m grating. With this it is then possible to photograph ten regions in the spectrum simul-

taneously, each 180 Angstroms long, although the cassettes must be separated by at least 50 Angstroms. The spectrograph slit is in the wall between two rooms, so that sources and control table are in one room, while the grating, focal plane table, and photographic loading and development equipment are in another.

The slit is provided with an electromagnetic shutter of concentric opening type and aperture 4 cm, placed behind the slit in order to be out of the way. This is operated by an electromagnetic clock which will automatically give any pre-determined exposure of from 1 to 100 seconds.

The light from the source is focused on the slit by a quartz-fluorite achromat of 25 mm aperture and 250 mm focal length, obtained from Bernhard Halle. This was tested in the range 2500–6000 Angstroms and was found to be exceptionally good, the total variation in focal length being not over 3 mm. As the arc ordinarily flickers by this amount, no correction need be applied for varying fractions of light of different wave lengths passing through the slit. An image of the arc magnified about six times was thrown on the slit, care being taken that the whole area of slit was at all times filled with light.

Fifteen exposures could be taken on each plate, eleven of these being used for photographing the spectrum under measurement, two for calibration of the plate, and two for its standardization. The term calibration is here used to denote the process of determining the d-log I curve of the emulsion at each wave length used, for the standard time of exposure. Standardization denotes the determination of the spectral energy sensitivity variations of the system (spectrograph-plate-development), in order that the characteristic curves could be linked together over widely separated wave-length intervals.

For calibration and standardization in the visible region a ribbon filament gas-filled tungsten lamp, operated at 6 volts and 20 amperes, was used. This was run from six 6 volt storage batteries connected in parallel, the whole being floated while in operation on the 110 v. dc system, with 15 amperes flowing in. In the ultraviolet region a quartz mercury arc was used, this being run always at 35 volts, 3 amperes for calibration, and 73 volts, 3.5 amperes for standardization, the greater energy input in the second case being desirable in order to have large deflections when standardizing the arc with the thermo-electric spectro-radiometer.[7] When photographing the high-voltage arc neutral screens were used to reduce its intensity.

[7] G. R. Harrison, J.O.S.A. & R.S.I., *11*, pp. 113, 341; 1925.
G. R. Harrison and G. S. Forbes, *ibid.*, *10*, p. 1; 1925.

In methods of photographic photometry in common use it is customary to take a series of spectrograms of some constant source whose light is varied by known steps. This variation is generally chosen so as to be neutral, i.e., proportional at all wave lengths. This is carried out by means of varying slit width (in the case of continuous sources), varying aperture, neutral filters, or wire screens.[2] Other methods, which have the great advantage that only one exposure is required for calibration instead of ten or twelve, involve the use of a "Stufenblende" or a "Raster." They require that the beam of light passing through them be uniform over its cross section, and need careful adjustment. Their chief advantage seems to be where long exposures are required. In the present work screens were used, but an arrangement was made whereby 40 calibration exposures could be put on each plate in the space occupied by two with the other methods. This involves a great increase in accuracy, since the greatest photometric errors are due to local variations in emulsion sensitivity, which can best be overcome by statistical methods. In front of the slot of each cassette were placed two diaphragms, one which could be folded down into place from above, and the other up from below. The first contains vertical slits 0.8 mm wide and 40 mm apart, and is used in making calibrations with the tungsten lamp. (For the mercury arc adjustable slits are used, which can be placed where the principal lines occur.) An exposure to the lamp is taken through this grid of slits, with normal light brightness. The plate is then moved 1.2 mm to one side by means of a single turn of a screw pressing against the end of the plate holder, and an exposure is taken through a screen of transmission 67%. This process is then repeated with all the screen combinations available, so that an intensity range of about 100 fold is covered in 11 steps. A second set of calibrations is then taken in reverse order, to neutralize any small drift in lamp brightness. The adapter may then be moved vertically to another position in the cassette, and the process repeated.

For standardization in the visible a similar lamp was used, run at lower temperatures. The slit width for this purpose was about 5 mm, the color contamination due to this wide slit being entirely negligible. The lower flap diaphragm was then folded up into place, the slits in this being 6 mm wide to avoid errors due to diffraction. Four exposures could be taken side by side, at four different standard lamp temperatures; this was then repeated on a different portion of the plate. A portion from the center of a typical plate is shown in Fig. 1.

The color temperatures of the standard lamps were measured by means of a disappearing filament pyrometer, the color temperature

being taken from the brightness-match temperature by means of Zwikker's data as given by Dorgelo.[2] The energy distribution in the range 6000-4000 Angstroms was then computed for each color temperature used by means of Wien's law, written for convenience in the form

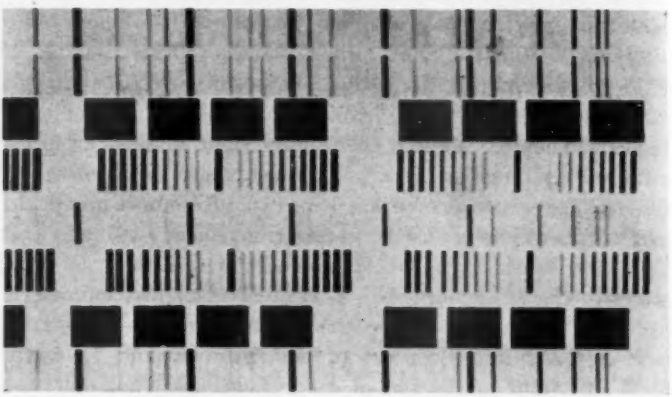

FIG. 1. *Portion selected from near the center of a typical plate showing (a) several exposures to multiplet No. 128; (b) calibrations with tungsten lamp and screens; (c) standardizations with tungsten lamp at different temperatures.*

$$\log J = 26 - 5 \log \lambda - \text{antilog}\,(7.7939 - \log \lambda - \log T).$$

As an additional check, the pyrometer was used to measure the color temperature of a lamp which had previously been calibrated at the Nela Research Laboratory in terms of current through the filament. The temperatures obtained agreed to within 5°.

The quartz mercury arc was used as a standard source between 4400 Angstroms and 2500 Angstroms. As the strong mercury lines average more than 180 Angstroms apart, three separate exposures were necessary to get at least three such lines on each plate, the cassettes being moved to right or left as required. Most of the mercury lines which appear as single maxima in the spectro-radiometer are resolved by the grating and some of these resolved lines are broader than others. Accordingly a fairly wide slit was used for these exposures, and the separate intensities of the lines in each maximum were added together.

The energy distribution of the mercury arc was measured by means of a spectro-radiometer containing lenses and prism of 50 mm aperture, which was in turn calibrated for transmission in all regions of the

spectrum between 2500 and 4400 Angstroms by means of photo-electric cells in glass and in quartz. A considerable change in transmission was found, especially below 3500 angstroms, indicating that neglect of this correction, as is frequently done, may be serious. In Fig. 2 is given the calibration curve of the spectro-radiometer together with a typical curve showing the sensitivity variation of the grating photometric system.

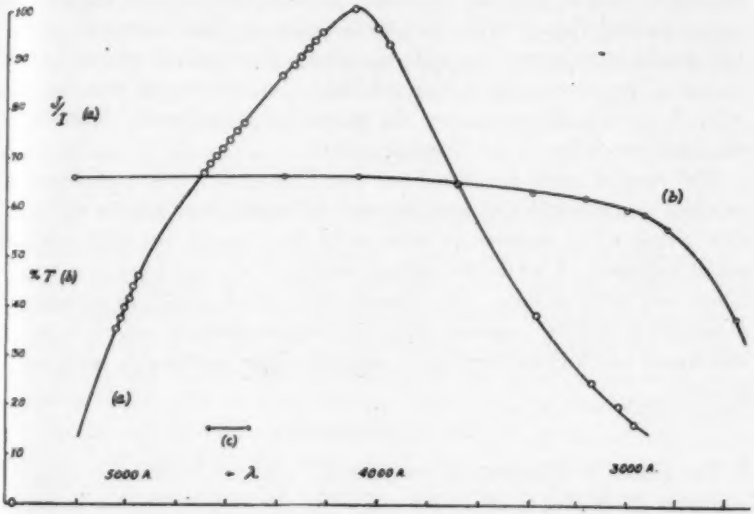

FIG. 2. *(a) Typical curve showing the variation of sensitivity (J/I) of the photometric system used, for unit plate density. The maximum sensitivity occurs in the violet, where the photographic plate (Eastman 36) is most sensitive. The rapid decrease of sensitivity in the ultraviolet is due largely to falling off of brightness of the grating, while that in the visible is mainly due to decreasing plate sensitivity. The shape of the curve in any particular case is due to a combination of effects of reflection coefficient of grating material, form of ruling of grating, astigmatism of mounting, characteristics of focusing lens, emulsion sensitivity, and development, and accordingly at least portions of it must be determined for each set of plates which are to be compared.*

(b) Transmission coefficient of the spectroradiometer to light of different wave lengths, as determined by means of photo-electric cells.

During the course of this and related work it was found that under certain conditions, wire screens of oxidized brass, commonly considered truly neutral, may not be so. This question is being discussed separately, and in the present work the conditions found necessary for strict neutrality were carefully observed. In addition to the screen curves comparison calibration curves were taken on most plates in selected wave-length

regions using neutral filters whose transmissions at the desired wave lengths were measured on the spectro-radiometer. The screens used have been repeatedly calibrated over a period of several years, and give consistent calibration curves.

In the region below 5000 Angstroms Eastman 36 plates were used, developed to approximately unit contrast with a minimum of fog. These show a very straight characteristic curve at most wave lengths, while several batches of Eastman 33 plates, perhaps more desirable in certain ways, showed curves with two distinct straight line portions. While this would introduce no error, it was undesirable as it would make the fitting of the curve slightly less definite. All development was for five minutes in Elon-Hydrochinon, the plates being constantly brushed to diminish errors due to the Eberhard effect.

The spectra were measured on the Comparator-Microphotometer recently described.[8] The spectrograph slit width was usually 0.3 mm, this giving a line sufficiently wide to be flat-topped, yet with not too much background, while the microphotometer slit was kept at a width about one-fifth of this. The closest lines which could be separately measured were 0.24 Angstrom apart. A supplementary method is being developed which gives promise of decreasing the measurable separation greatly.

THE LIGHT SOURCE

The source of light was an arc between titanium carbide or metallic titanium electrodes in air at low pressure, this being variable between 1 cm and atmospheric. The carbide used was some material obtained through the kindness of the General Electric Company, a small amount of iron being the only sensible impurity. The titanium metal had a greater amount of iron and a few other impurities, but as much less self-reversal occurred under given conditions with the metal than with the carbide, the former was used in a number of exposures, corrections being applied when necessary for impurity lines. It was never found possible to eliminate self-reversal completely in all multiplets with the carbide, even with currents less than 1 ampere, while with the metal the self-reversal was generally negligible if the current was below 1.5 amperes, at the low pressures used.

The arc container consisted of a 1.5 liter Pyrex flask with two side arms containing internally water-cooled electrodes fastened in place with sealing wax. The electrodes were fitted with coarse vacuum tight

[8] G. R. Harrison, J.O.S.A. & R.S.I., *16*, p. 63; 1928.

double threads, so that the arc length could be easily controlled while in operation. To the neck of the flask was waxed a plane crystal-quartz window which remained satisfactorily cool. Under ordinary running conditions the windows remained clear for several hours, and a number of these low pressure arcs were provided so that one with a clear window would be always available.

The arc was run on 110 v. dc, with series rheostat and a large reactance to cut down fluctuations. The voltage across the arc could be adjusted to any value between 20 and 80 volts, while the arc current was generally between one and three amperes. Below one ampere the arc became very unstable, especially when metallic electrodes were used. It was not found practicable to use pressures below 3 cm on account of the increasing strength of bands.

REDUCTION OF DATA FROM PLATES

Microphotometer measurement of a plate results in a series of galvanometer readings taken with the light shining through the various lines to be measured in the multiplets, through the continuous background in the neighborhood of these lines, and through the various calibration and standardization exposures, the light having first been adjusted to give 100 cm deflection through a clear portion of the plate. The calibration deflections were plotted directly against screen transmissions on two-cycle logarithmic coördinate paper, giving a curve similar to the common characteristic curve, but inverted. A curve of this kind could be plotted for every 25 Angstroms in the visible, for approximately every 300 Angstroms in the ultraviolet between 4000 and 3000 Angstroms, and for closer intervals below this down to 2500 Angstroms. As the characteristics of most photographic emulsions change quite slowly in the region 5000–2500 Angstroms,[9] and as the general characteristics of the Eastman 36 emulsion used are now well known from data collected from numerous plates, determination of plate characteristics at these intervals was sufficient. It was usually possible to use a single contrast value for the whole of each plate, since only changes in speed were large, except in transition regions similar to those near 5100 and 2500 Angstroms. A set of calibration curves was measured near each end of each plate, and as each set contained four curves from independent exposures, very smooth calibration curves resulted.

[9] G. R. Harrison, J.O.S.A. & R.S.I., *11*, p. 341; 1925.

The galvanometer deflection for each line was then converted into its corresponding intensity J by means of the proper calibration curve, this also being done for the background in the clear space nearest to the line. The background intensity was then subtracted from each line intensity, together with any correction which might be necessary for ghost laps from neighboring lines.

The standardization exposures were next converted into apparent intensities from the same curves, giving a series of J values for the standard lamp, at 25 Angstroms intervals in the visible. In the ultraviolet this was done for each of the mercury lines on each plate.

The true intensities I of the standard lamp were obtained from its calibration curves. The curve relating the ratio J/I to wave length was then drawn for the spectral region it was desired to cover (see Fig. 2a), and J/I values for intermediate wave lengths were taken from this. Since three to eight such curves could be plotted for each plate or set of plates, very good average values for J/I were obtained. Finally, J for each spectral line to be measured was divided by the J/I value for its wave length, giving the true intensity I of the line.

The procedure outlined above involves little new but is given as a general method which serves to compare the intensities of two lines taken in exposure at the same time, no matter what their wave-length separation, or whether they are on the same plate or the same kind of plate, or developed together or not. It is a null method, and can be used in the infrared, visible, and ultraviolet regions at the same time. The details as given here are similar to those developed by Ornstein and his collaborators in the visible, and by the writer in the ultraviolet, with certain modifications designed to increase accuracy and ease of use.

SOURCES OF ERROR

All transmission variations of the focusing lens, grating spectrograph, etc., are eliminated provided the standard lamp is placed in the same position as the light source to be measured, and the slit is completely filled with light in both cases. The effect of increased dispersion at longer wave lengths is to make the flat-topped line images broader and less high there, while the continuous spectrum of the standard lamp is made proportionately weaker. The exposures to the spectra being measured need only be of approximately equal times, although in the case of the mercury arc standardization, and all calibrations, they must be accurately equal. The electromagnetic shutter is uniform to 1/10

second. The microphotometer itself has an error well under 1%, although variations in setting reduce this somewhat, so that 2% is the average deviation on repeat readings. Variations in emulsion over the surface of the plate, and differences in development, are about 5%, though this error is very greatly reduced by the number of points contributing to the various curves and to the line intensities themselves.

It was at one time feared that intermittency effect might cause an error. It seems impossible to prevent the arc from flickering somewhat, and although an observer kept the image constantly on the slit, decided variations in intensity were observable inside the grating room. An investigation by a student in this laboratory[10] indicated that a partial intermittency effect of this sort, of comparatively long period, is negligible. Also, the screens used for calibrating, even when placed so as to reduce intensity variations to a minimum, produce some intermittency effect, which probably largely compensates for the other.

Many of the multiplets listed in this paper have been measured over 100 times. The writer has come to the conclusion that an accuracy better than 1% is attainable using photographic plates, provided the methods used are simple enough so that a large amount of data can be collected. That the results listed here vary more than this amount is due to factors not inherent in the photometric method.

The titanium spectrum is a very "dirty" one, the background being filled with thousands of fine lines, many being probably weak titanium lines not yet identified as such, others being due to small traces of impurities, while the majority are band lines of various compounds. These change in intensity greatly with excitation conditions, particularly pressure, with the result that it is not possible to get an accurate value for the background correction under a line. In the case of the very strong multiplets this error has small effect, but the great majority of titanium multiplets are of such intensity that these errors become very great. With the wide slit necessary for this method the background becomes relatively stronger, and large background corrections introduce large errors.

The writer is now investigating the possibilities of a method of photographic photometry less exact than the one outlined here, but more rapid and flexible, which could be used to supplement it, and which would involve the use of a very narrow slit. In this way the errors due to background will be reduced, and it is thought that this will more

[10] C. E. Weinland, J.O.S.A. & R.S.I., *15*, p. 337; 1927.

than compensate for the lack of photometric accuracy. It is proposed to use this method for investigating which of the remaining Ti multiplets contain exceptions to the intensity formulas.

SELF-REVERSAL

Frerichs[5] has measured the relative intensities of lines in certain multiplets of a number of elements of the iron group, including four of Ti I. He found that self-reversal could be completely eliminated by using currents in the metallic arc burning at a pressure of 3 cm and currents of from 1–5 amps. Van Milaan found that in a ^5FD multiplet of iron he was almost able to eliminate self-reversal by using currents of 0.45 amp in the Pfund arc at atmospheric pressure. When currents of 4 to 5 amps were used, much self-reversal was present. This was shown by the fact that the stronger lines were all relatively weaker than the values called for by the multiplet formulas, but when to each intensity was added a fraction proportional to this intensity moderate agreement was obtained with the sum rule, though not, for this multiplet, with the formulas.[11]

We may assume that the amount of self-reversal in a line belonging to a given multiplet having narrow separations is proportional to its intensity. Then the intensity I_m for a given line emerging from the source will be less than the intensity I_e which would emerge if self-reversal did not exist by an amount $I_e^2 r$, where r is a constant for the multiplet. Then $I_m = I_e(1 - I_e r)$. This formula cannot be rigorously true, but is a reasonable approximation for small values of r. Its breakdown is connected with the failure of the exponential law of absorption when a finite layer of absorbing medium is traversed, since we are measuring only the total area of the absorption curve for a layer of unknown thickness, and not the actual shape of the curve. Since after a moderate amount of absorption has taken place there is relatively less light left to be absorbed in the center of the line, the area of the absorption curve would be expected to be less than the exponential law would indicate. That the approximate formula given holds good, and that the departure from this formula goes in the right direction, is indicated by the results obtained for a large number of multiplets, of which Fig. 3 gives an example.

The multiplet $a^5F' - b^5G'$ (No. 128 in Russell's list for Ti I) arises from metastable states about 6500 wave number units above the lowest level of the normal atom. It has been found to obey the intensity

[11] J. B. van Milaan, ZS. f. Phys., *38*, p. 427; 1926.

formulas very closely (see Table 3), and contains principal lines and first order satellites all of sufficient strength to be easily measured. It covers a comparatively narrow spectral range and can be obtained with or without self-reversal quite readily. In Fig. 3b and c the common logarithms of the computed intensities for this multiplet, taken from Russell's tables (the value 456 given there for the strongest line is a misprint, and should read 546), are plotted as ordinates log I_c, while

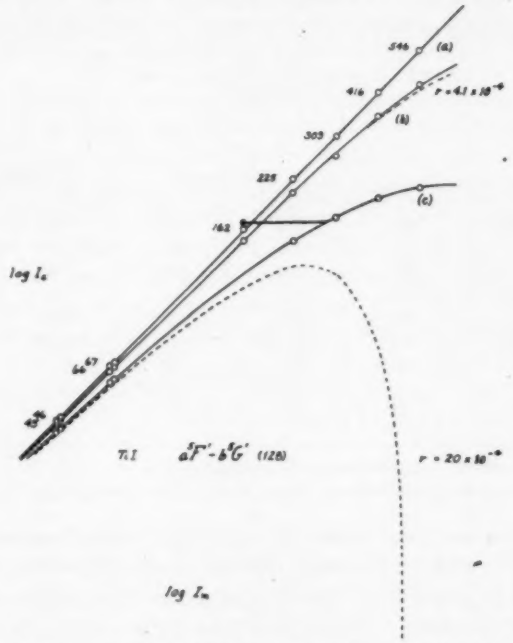

FIG. 3. (a) *The common logarithms of the intensities of the stronger lines of multiplet No. 128,* $a^5F'-b^5G'$ *as calculated from the intensity formulas, are plotted against themselves.*

(b) *They are plotted against the logs of the measured intensities (solid curve) when a moderate amount of self-reversal is present. The theoretical self-reversal formula (dotted curve) deviates from this only for the strongest lines.*

(c) *With more self-reversal, the deviation becomes much greater.*

log I_m values, plotted as abscissas, are taken from the relative line intensities as measured under two conditions of current, voltage, and arc pressure (solid curves). A curve similar to one of these was first plotted giving one of the weaker lines the value assigned to it in Russell's tables, the approximate amount of self-reversal present in the strongest line being calculated from this. The I_m values were then recalculated

on the supposition that the weak line had an amount of self-reversal proportional to this, and a new curve was plotted. In this way by a series of successive approximations (actually only two calculations were necessary) the proper value for the weak line was reached. The value of r in the formula was then calculated for each line, and it was found that r decreased with increasing intensity. For most of the weaker lines, however, it had a constant value, and this value was used in calculating the dotted curve for each solid curve. Typical data used for plotting these curves is given in Table 1. It is seen that in one case

TABLE 1. *Typical self-reversal data for $a^5F'-b^5G'$.*

Line λ	I_e	I_r	I_m	I_r	I_m
		$r=4.1\times10^{-4}$		$r=20\times10^{-4}$	
4981.75 A.	546	424	432	−49	214
4991.08	416	345	352	69	204
4999.51	309	270	279	118	177
5007.22	225	208	204	124	148
5014.28	162	151	(222)*	109	(163)*
5020.04	67	65.2	65.8	58.0	61.5
5022.87	66	64.3	63.9	57.3	59.2
5016.17	46	45.0	(48.8)*	41.7	(48.0)*
5024.85	45	44.2	44.6	41.0	41.0

I_r denotes intensity computed from self-reversal formula.
* The values in parenthesis belong to lines having other lines superposed (laps).

the departure from the values (I_r) given by the self-reversal formula are negligible, while in the other case the formula is valueless.

It should be pointed out that this procedure is necessary only to give an experimental basis to the self-reversal curve and to show that it is qualitatively correct as a first approximation. In actual practice it is sufficient to plot log I_m against log I_e giving the weakest line any desired value; if all lines in the multiplet obey the intensity formula a smooth curve of the general shape indicated by the figure will result. In certain cases, however, where satellites are much weaker than main lines, with no points on the curve between the two groups, it is difficult to determine whether or not one set of lines is too weak or too strong. Where self-reversal cannot be eliminated this difficulty can often be overcome by plotting several neighboring multiplets from the same lower state on the same self-reversal curve, when a sufficient number of normal lines is generally found to settle the question.

That self-reversal may become a boon in certain cases is indicated where abnormally high intensities have been found, their departure from the normal curve varying with experimental conditions. This indicates the presence of an unknown line from an impurity, or from a different lower level in the atom, lapped on the abnormal line. For this reason all of the multiplets listed below have been measured under varying conditions of self-reversal, and where the measured intensity, after correction from the self-reversal curve, was found abnormal but constant under varying conditions of self-reversal, the line was considered as truly departing from the intensity rules.

RESULTS

In Table 2 are given typical sets of values of I_m for the multiplet whose intensities are plotted in Fig. 3. These were chosen from a large number as having approximately the same self-reversal, and indicate the amount of variation present in the results before averaging. The weakest line has been set always at the value 45, the actual intensity of this line varying ten-fold. A small part of the variation is due to different amounts of self-reversal, but most of it comes from uneven background and varying plate sensitivity. The data given in this table

TABLE 2. *Multiplet No. 128 of Ti I.* $a^3F'-b^3G'$.

Plate I_c / I_m	546	416	309	225	162	67	66	46	45
81a–4	432	341	269	204	lap	68.8	67.0	51.0	45
84d–11	428	367	286	221		67.4	65.0	48.6	45
80a–13	423	341	286	196		66.5	64.0	48.0	45
80a–12	413	342	251	184		67.0	65.0	51.0	45
80a–3	413	334	237	183		61.8	60.5	47.6	45
80a–4	411	345	253	198		66.0	66.1	54.0	45
Mean	420	345	263	198	lap	66.2	64.6	50.0	45
Ave. dev. % ±	1.8	2.1	6.3	5.0	—	4.0	2.4	2.6	—

indicate a large amount of self-reversal under the conditions used; other tables were filled out for different amounts of self-reversal. Each table furnished a series of points along which a smooth curve was drawn, the measured intensities corrected for self-reversal being obtained from the curve by reading the I_c value corresponding to the I_m value for each point. The resulting I values were then averaged for the different curves, giving the results listed in the following tables.

These tables are listed in descending order of wave length of the multiplets for the different systems, the number in parenthesis being

that assigned to the multiplet in Russell's paper. The first column contains the wave length of the line, the second and third the inner quantum numbers of the two terms producing it, the fourth gives the line intensity as estimated by King (in the case of Ti II lines the intensities in the spark are given). The fifth column gives the line intensity calculated from the intensity formulas, and the sixth the line intensity as measured. In the three multiplets which have been previously measured by Frerichs, his values have been included in a separate column preceding this. Where the Zeeman effect has been measured the seventh column contains a symbol indicating whether the pattern is normal or not.

TABLE 3. (128) $a^5F'-b^5G'$ *Class II.*

λ	a^5F'	b^5G'	I_k	I_c	I_m	Z
5024.85	2	2	20	45	45	n
5022.87	3	3	25	66	64.9	n
5020.04	4	4	25	67	67.1	n
5016.17	5	5	20	46	48.5*	n
5014.28	1	2	(25)	162	160ca†	n
5007.22	2	3	40	225	225	n
4999.51	3	4	45	309	308	n
4991.08	4	5	50	416	413	n
4981.75	5	6	60	546	548	n

* Variation indicates unknown line or band lap. Found entirely normal on some plates.
† Corrected for lap $a^5F'_5$—$a^5D'_1$, sum of two being normal.
Intervals normal.
Second order satellites too weak to measure, but look normal.

TABLE 4. (163) $a^5P'-a^5D'$ *Class III.*

λ	a^5P'	a^5D'	I_k	I_c	I_m	Z
4656.06	3	2	6	4	—	—
4650.02	2	1	10	9	9	n
4645.19	1	0	12	12	12	n
4639.94	1	1	15	27	27	n
4639.66	3	3	15	28	28	n?*
4639.36	2	2	18	35	35	n
4629.34	1	2	15	21	21	n
4623.10	2	3	25	56	56	n?
4617.27	3	4	30	108	108	n?

* n? signifies Zeeman measurements incomplete, or small discrepancy between observation and theory.
Intervals normal.

TABLE 5. (172) $a^5F'-b^5F$ *Class II.*

λ	a^5F'	b^5F	I_h	I_c	*I Frerichs*	I_m	*Z*
4555.50	5	4	30	53	54.5	53	n
4552.45	4	3	35	75	80	75	n
4548.77	3	2	35	72	77	71	n?
4544.70	2	1	30	48	50.5	48	n
4536.00	1	1	40	96	92	90 *	n
4535.92	2	2	40	120	118	115	n
4535.58	3	3	50	189	191	190	n
4534.78	4	4	60	304	307	305	n
4533.25	5	5	80	475	475	472	n
4527.32	1	2	35	48	50	48	n
4522.80	2	3	40	72	76.5	72	n
4518.03	3	4	50	75	79.5	74	n
4512.74	4	5	40	53	53	54	n

* It is believed that these two lines are normal, but their sum often appeared low. This is perhaps a photographic phenomenon.

Intervals normal.

TABLE 6. (181) $a^5P'-b^5P$ *Class III.*

λ	a^5P'	b^5P	I_h	I_c	I_m	*Z*
4496.15	3	2	20	56	56	n?
4489.10	2	1	20	54	54	n?
4481.27	3	3	30	112	114	n
4480.61	2	2	5	10	10	n
4479.70	1	1	9	18	18.6	n
4471.24	1	2	20	54	56	n
4465.80	2	3	20	56	56	n

Intervals slightly abnormal.

TABLE 7. (209) $a^5F'-c^5D'$ *Class II.*

λ	a^5F'	c^5D'	I_h	I_c	*I Frerichs*	I_m	*Z*
4305.91	5	4	60	220	220	220	n
4301.08	4	3	50	150	132	120	abn?
4300.55	3	2	50	96	96	95	abn
4298.67	2	1	40	56	58	56	n
4295.75	1	0	22	28	28	28	n
4290.93	1	1	22	28	28	28	n
4289.08	2	2	25	40	39	39	n
4287.41	4	4	22	30	29	30	n
4286.01	3	3	25	42	37	33	abn
4281.40	1	2	10	4	—	4	n
4274.60	2	3	15-lap	4	—	—	—
4272.44	3	4	8	2	—	—	abn

$c^5D'_4-c^5D'_3$ interval abnormal.

TABLE 8. (237) a^5F-a^5G *Class III.*

λ	a^5F	a^5G	I_h	I_c	I_m	Z
4030.53	5	6	25n	546	546	abn
4026.54	4	5	25n	416	406	abn
4021.87	3	4	25n	309	312*	—
4017.78	2	3	15n	225	224	—
4015.40	1	2	12n	162	162	—

Remaining lines too weak to measure.
* Ghost lap correction.
a^5G intervals abnormal.

TABLE 9. (36) $a^4P'-a^4D'$ *Class V.*

λ	a^4P'	a^4D'	I_h	I_c	I_m	Z
4330.71	3	2	0	3	5	n?
4320.95	2	1	1	5	8	n
4314.98	1	1	40	25	Lap	n?
4312.88	3	3	35	27	17±5	n
4307.89	2	2	40	32	28	n
4301.93	1	2	15	25	25	n?
4300.05	3	4	60	120	132	n?
4290.23	2	3	50	63	44	n?

Note disagreement between measurements and King's estimates, being in some cases on opposite sides of the theoretical values. Great variation of λ4313 seems to indicate that unknown line is superposed on it. There is some indication of this also on λ4308.
a^4P' intervals abnormal; a^4D' intervals abnormal.

TABLE 10. (60) $b^4F'-a^4G'$ *Classes III, IV & V.*

λ	b^4F'	a^4G'	I_h	I_c	I_m
3513.08	4	3	tr	1	—
3500.33	3	3	2	29	22
3491.05	2	3	10	180	180
3489.74	4	4	2	38	28
3477.18	3	4	15	241	245
3476.99	5	5	tr	29	
3461.50	4	5	20	321	322
3444.31	5	6	30	420	410

Intervals practically normal.
No Zeeman measurements.

TABLE 11. (68) $a^4F'-a^4G'$ *Classes II, III & IV.*

λ	a^4F'	a^4G'	I_h	I_c	I_m
3409.80	4	3	4	1.0	—
3407.20	5	4	3	.8	—
3394.57	3	3	40	29	28
3387.83	4	4	50	38	38
3383.76	2	3	125	180	178
3380.28	5	5	30	29	29
3372.80	3	4	100	241	236
3361.22	4	5	125	321	320*
3349.41	5	6	125	420	420

* Corrected for lap $a^3F'_3-d^3D'_3$.
Intervals practically normal.

TABLE 12. (74) $b^4F'-a^4F$ *Class III.*

λ	b^4F'	a^4F	I_h	I_c	I_m
3348.82	3	2	10?	38	65-lap
3346.72	4	3	15	51	50
3343.76	5	4	10	40	39
3340.33	2	2	35	154	154
3335.19	3	3	40	198	200
3329.45	4	4	70	293	290
3326.76	2	3	20	38	42-lap
3322.93	5	5	75	440	440
3318.01	3	4	10	51	46
3308.79	4	5	8	40	39

Intervals practically normal.

TABLE 13. (79) $b^4P'-b^4D'$ *Classes IIIr, IV & V.*

λ	b^4P'	b^4D'	I_h	I_c	I_m
3288.58	2	1	5	3	9
3288.42	3	2	5	5	
3282.32	1	1	25	25	25
3278.28	2	2	30	32	32
3272.06	1	2	25	25	24
3271.63	3	3	25	27	27
3261.59	2	3	60	63	138-lap
3248.60	3	4	50	120	122

Intervals practically normal.

TABLE 14. (85) $a^4F'-a^4F$ *Class IIIr.*

λ	a^4F'	a^4F	I_h	I_c	I_m
3254.23	5	4	30	40	40
3252.85	4	3	40	51	72
3251.89	3	2	30	38	39
3241.97	2	2	60	154	154
3239.03	3	3	60	198	195
3236.57	4	4	70	293	285
3234.52	5	5	75	440	450
3229.18	2	3	40	38	40
3222.82	3	4	35	51	58-lap
3217.04	4	5	30	40	43

Intervals practically normal.

TABLES 15. (96) $b^4F'-a^4D'$ *Classes III & IV.*

λ	b^4F'	a^4D'	I_h	I_c	I_m
3168.52	5	4	40	250	249
3162.56	4	3	35	171	168
3161.76	3	2	30	112	112
3161.19	2	1	25	70	72
3155.65	4	4	12	29	30
3154.18	2	2	12	28	28
3152.24	3	3	15	37	35

b^4F' intervals normal; a^4D' intervals abnormal.

TABLE 16. (106) $a^4F'-a^4D'$ *Classes III & IV.*

λ	a^4F'	a^4D'	I_h	I_c	I_m
3088.03	5	4	75	250	245
3078.64	4	3	50	171	168
3075.22	3	2	40	112	110
3072.97	2	1	40	70	70
3072.10	4	4	30	29	29
3066.36	2	2	20	28	61*
3066.20	3	3	30	37	
3059.73	3	4	4	14	3
3057.43	2	3	10	2	5

* Corrected for lap.

a^4D' intervals abnormal; a^4F' intervals normal.

TABLE 17. (70) a^3G—a^3H *Classes II & III.*

λ	a^3G	a^3H	I_k	I_c	I_m
5996.01	4	4	2	10	<20
5988.58	5	5	2	10	<20
5978.54	3	4	25	194	194
5965.83	4	5	30	240	242
5953.16	5	6	30	296	291

Intervals practically normal.

TABLE 18. (72) a^3P'—b^3D' *Classes II & IIIA.*

λ	a^3P'	b^3D'	I_k	I_c	I_m	Z
5980.89	2	1	(1)	1	—	—
5937.79	2	2	6	15	5	abn
5922.11	0	1	18	20	20	n
5899.29	1	2	25	45	46	abn
5866.45	2	3	35	84	85	n
5941.73	1	1	12	15	15	n

b^3D' intervals slightly abnormal.

TABLE 19. (112) a^3F'—a^3F *Classes I & IA.*

λ	a^3F'	a^3F	I_k	I_c	I_m	Z
5252.11	4	3	8	81	—	n
5219.72	3	2	8	80	48	abn
5210.39	4	4	40	1215	1210	n
5192.98	3	3	35	847	844	n
5173.74	2	2	30	640	631	n
5152.18	3	4	10	81	81	n
5147.48	2	3	10	80	84	n?

Self-reversal never completely eliminated, but long-wave satellites appear definitely weak. a^3F intervals abnormal.

TABLE 20. (123) b^3F'—d^3G' *Classes II & III.*

	b^3F'	d^3G	I_k	I_c	I_m	Z
5071.49	4	4	7	63	62	n
5066.01	3	3	7	63	63	n?
5038.41	2	3	25	720	720	n
5036.47	3	4	25	945	950	n
5035.92	4	5	25	1232	1220	n

Intervals slightly abnormal.

TABLE 21. (126) $a^3F'-a^3D'$ *Class I.*

λ	a^3F'	a^3D'	I_h	I_e	I_m	Z
5064.66	4	3	25	405	400	n
5039.96	3	2	22	280	280	n
5014.19	2	1	(25)	189	185*	—
5009.65	3	3	7	35	29†	n?
4997.10	2	2	8	35	35	n?
4967.30	2	3	(1)	1	—	—

* Corrected for lap of a ${}^5F'_1-b^5G'_2$.

† As self-reversal was never completely eliminated from this multiplet, it is possible that the last line in the table should be 42 and the one above it 35, though that this is less probable than the values given above is indicated by comparison with self-reversal curves of neighboring multiplets photographed simultaneously.

a^3D' intervals abnormal.

TABLE 22. (138) a^3G-b^3H *Classes III & IV.*

λ	a^3G	b^3H	I_h	I_e	I_m	Z
4925.42	4	4	5	10	10	n?
4915.24	5	5	5	10	10	n?
4913.63	3	4	20	194	190	n
4899.93	4	5	20	240	240	n
4885.09	5	6	20	296	300	n

Intervals practically normal.

TABLE 23. (141) $a^3H'-a^3I'$ *Classes III & IV.*

λ	a^3H'	a^3I'	I_h	I_e	I_m
4893.06	5	5	2	14.3	—
4882.34	6	6	2	14.3	25
4870.14	5	6	20	500	540
4868.28	4	5	18	421	465
4856.01	6	7	20	594	594

Large background corrections, and numerous underlying bands.

a^3H' intervals abnormal, a^3I' intervals normal.

TABLE 24. (148) $c^3P'-b^3D'$ *Class III.*

λ	c^3P'	b^3D'	I_h	I_e	I_m	Z
4812.25	2	2	5	15	19*	—
4805.43	2	3	12	84	84	n?
4797.99	1	1	5	15	14	n?
4796.22	0	1	6	20	20	n
4792.50	1	2	10	45	45	n?

* Variation indicates lap by unknown line.
Accuracy not high because of large background correction.
Intervals very abnormal.

TABLE 25. (153) $a^3H'-c^3H$ *Class III.*

λ	a^3H'	c^3H	I_h	I_e	I_m
4769.78	6	5	4	3.2	4.3
4766.33	5	4	4	3.2	4.4
4759.28	6	6	25	114	114
4758.13	5	5	25	93	94
4747.69	5	6	3	3.2	3.4
4742.80	4	4	20	78	48
4734.68	4	5	3	3.2	3.2

Large background and band corrections. Long wave-length satellites are lapped with bands, but look really stronger than short ones.
a^3H' intervals abnormal; c^3H intervals normal.

TABLE 26. (157) $a^3F'-a^3G'$ *Class I.*

λ	a^3F'	a^3G'	I_h	I_e	I_m	Z
4715.31	4	4	4	63	63	—
4693.68	3	3	5	63	63	—
4681.91	4	5	30	1232	1220	n
4667.59	3	4	25	945	940	n
4656.47	2	3	25	720	720ca*	n

* Line lap correction.
Self-reversal was not eliminated enough to make sure satellites were correct relative to main lines, but curves look normal.
Intervals normal.

TABLE 27. (233) $a^3P'-c^3P$ *Class III.*

λ	a^3P'	c^3P	I_h	I_c	I_m	Z
4082.46	2	1	20	10	10	n
4078.47	2	2	30	30	30	n
4065.11	1	0	15	8	8	n
4064.22	1	1	15	6	6	n
4060.27	1	2	20	10	10	n
4055.02	0	1	20	8	8	n

c^3P intervals abnormal.

TABLE 28. (239) $a^3F'-b^3F$ *Class II.*

λ	a^3F'	b^3F	I_h	I_c	I^* *Frerichs*	I_m	Z
4024.57	4	3	35	81	160	118	n
4008.94	3	2	35	80	125	98	abn
3998.65	4	4	100R	1215	1215	1210	abn
3989.77	3	3	80r	847	865	850	n
3981.77	2	2	70r	640	654	640	abn
3964.27	3	4	35	81	88	82	abn
3962.85	2	3	35	80	86	80	abn

Intervals normal.

* There is obviously some self-reversal remaining in Frerich's values, and if the value 86 is set at 80 the agreement is better.

TABLE 29. (246) $a^3F'-b^3D'$ *Class II.*

λ	a^3F'	b^3D'	I_h	I_c	I_m	Z
3958.21	4	3	80	405	405	n
3956.28	3	2	60	280	200	abn
3948.66	2	1	60	189	190	n
3929.87	2	2	40	35	44	abn
3924.51	3	3	50	35	55	n
3898.49	2	3	8	1	—	—

b^3D' intervals abnormal.

TABLE 30. (271) $a^3F'-c^3F$ *Class I.*

λ	a^3F'	c^3F	I_k	I_c	I_m	Z
3771.64	4	3	25	81	118	n
3753.63	3	2	25	80	116	abn?
3752.87	4	4	80r	1215	1210	n
3741.06	3	3	60r	847	850	n
3729.77	2	2	50r	640	640	n
3722.58	3	4	15?	81	150-lap	abn.
3717.39	2	3	20	80	80	—

c^3F intervals somewhat abnormal.

TABLE 31. (276) $a^3P'-b^3S'$ *Class III.*

λ	a^3P'	b^3S'	I_k	I_c	I_m
3725.12	2	1	20	5	5
3709.95	1	1	20	3	3
3702.29	0	1	10	1	1

Intervals normal.

TABLE 32. (284) $a^3F'-b^3G'$ *Class I.*

λ	a^3F'	b^3G'	I_k	I_c	I_m
3687.38	4	3	5	1	—
3671.66	4	4	20	63	63
3658.14	3	3	20	63	63
3653.49	4	5	100r	1232	1150
3642.68	3	4	80r	945	940
3635.47	2	3	80r	720	720

b^3G' intervals slightly abnormal.

TABLE 33. (319) $a^3F'-d^3D'$ *Class II.*

λ	a^3F'	d^3D'	I_k	I_c	I_m
3385.93	4	3	40r	405	340*
3377.57	3	2	30r	280	400-lap
3370.42	2	1	40r	189	190*
3361.27	3	3	40r	35	lap
3358.26	2	2	10	35	35*
3342.14	2	3	6	1	12*

* Obtained assuming same self-reversal as No. 320, which arises from same lower state and a very close upper state to this multiplet. Corrected for ghost laps. Varying amounts self-reversal used, but never completely removed.

Accuracy very low, due to strong bands present when self-reversal was low, and to numerous line laps and close lines.

Intervals d^3D' somewhat abnormal.

TABLE 34. (320) $a^3F'-c^3G'$ *Class I.*

λ	a^3F'	c^3G'	I_h	I_e	I_m
3385.66	4	3	12	1	55
3379.20	4	4	15	63	63
3371.44	4	5	80r	1232	1230†
3361.00	3	3	10	63	63*
3354.64	3	4	60r	945	940†
3341.87	2	3	50r	720	**

*Variable relative to 3379.20 due to underlying bands, but appears equal to it.

** Exact lap with $a^3F'_3-a^3G'_4$, sum of two being about 20% below sum estimated, though this deviation may be spurious due to difficulties of measurement.

† Estimated from self-reversal curves.

This multiplet was difficult to measure, due to underlying bands, close lines necessitating use of narrow slit, and numerous laps.

Intervals practically normal.

TABLE 35. (347) $a^3F'-d^3G'$ *Class I.*

λ	a^3F'	d^3G'	I_h	I_e	I_m
3214.23	4	4	12	63	68-lap
3203.82	3	3	15	63	63
3199.91	4	5	100r	1232	1220
3192.00	3	4	80r	945	935
3186.45	2	3	60r	720	720

Intervals practically normal.

TABLE 36. (382) $a^3F'-e^3F$ *Class II.*

λ	a^3F'	e^3F	I_h	I_e	I_m
2967.22	4	3	25	81	87*
2956.80	3	2	25	80	86*
2956.13	4	4	70R	1215	1220
2948.25	3	3	60r	847	840
2941.99	2	2	60r	640	640
2937.30	3	4	25	81	81
2933.53	2	3	25	80	79

* Probably normal, but difficult to measure accurately.

Intervals practically normal.

CONCLUSIONS

Of all the multiplets measured in Ti I, 58% were found to obey the intensity formulas to well within 5%, and evidence was obtained in favorable cases which indicated that exact agreement could be expected when line separations were small. In Ti II, 62% of the multiplets measured were normal. In Ti I, of the 42% abnormal multiplets, 71% of the lines were normal, while 16% were abnormally weak and 13% abnormally strong. For the ionized atom, of the 38% abnormal multiplets, 61% of the lines were normal, while 21% were abnormally weak, and 18% abnormally strong. Of all the lines measured, 86% appeared to obey the intensity formulas, while 7.6% were too weak and 6.4% were too strong.

In agreement with the results of Frerichs for selected multiplets of elements of the iron group in general, no certain correlation was found in titanium between departures from the intensity formulas and from Lande's interval rule. Of 17 multiplets having abnormal intervals in their terms, 10 showed departure from the intensity formulas, although with no definite internal correlation. On the other hand, there were four multiplets with normal intervals and abnormal intensities, and 13 with normal intervals and normal intensities. While there is a small correlation, it is thought to be accidental.

While Zeeman patterns have not been determined for many of the lines measured, Russell's papers[1] give data for a number. In 11 multiplets whose lines show normal Zeeman patterns there are no departures from the intensity rules in nine, while two show departures. In seven multiplets containing lines whose Zeeman patterns are in some cases abnormal, there are six containing abnormal intensities and one whose main lines are all normal, but whose satellites have not been measured. Looking at individual lines, we find 84 having Zeeman patterns and intensities both normal, nine having both abnormal, nine having abnormal intensities and normal Zeeman patterns (six of these, however, being in one multiplet), and six having abnormal Zeeman patterns and normal intensities. Only those Zeeman patterns have been called abnormal which are marked abn. in the tables, those marked n?, which have only small departures from the normal separations, being treated as normal. The correlation here is again very low.

It should of course be born in mind that the intensity measurements are relative within a multiplet, and in most cases only deviations in one direction or the other are found. The policy has been to give the

majority in a multiplet the benefit of the doubt; thus if a multiplet contained five lines normal relative to one another, and two stronger lines (and these perhaps not normal relative to each other,) the two latter were termed abnormal. It is conceivable, however, that one of the stronger lines is truly the normal one, the other lines all being abnormally weak. This view seems necessary if we are to explain all anomalous intensities as being due to energy abstracted from the lines by intersystem combinations, as was shown to be the case in certain simple spectra by Ornstein and Burger.[12] The writer is at present of the opinion that this effect will explain many of the anomalies but not all, other perturbation effects entering which produce lines which are too strong as well as those which are too weak. A quantitative study of this matter is being undertaken in this laboratory.

It seems desirable to postpone a discussion of possible regularities in departures from the intensity formulas until some of the weaker multiplets of Ti have been measured, and homologous lines of neighboring elements compared with those of titanium. Results of measurements on the relative intensities of the stronger multiplets of this element will appear shortly.

This investigation has been greatly aided by a grant from the Rumford Fund of the American Academy of Arts and Sciences. It is a pleasure also to record my indebtedness to my associates in this laboratory, particularly Messrs. Harry Engwicht and Seth H. Neddermeyer, who assisted in making a number of the measurements and computations.

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PALO ALTO, CALIFORNIA.
SEPTEMBER 6, 1928.

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THE CONTINUOUS SPECTRUM OF MERCURY

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ABSTRACT

The continuous band spectrum of mercury vapor was observed (1) when a drop of mercury was kept rolling in a heated cylindrical quartz tube by means of a horizontal to and fro motion of the tube; (2) when the same tube in an electric oven was excited to luminosity by a high frequency electrodeless discharge. By the electrodeless method, with temperatures ranging from 160°C to over 200°C, and a controlling spark-gap of the order of 1 cm conditions were favorable for the continuous emission, while a greater temperature range was permissible in the first method. In each case the three well-known continuous bands with maximum intensities in the neighborhood of λ4600, λ3300, λ2536, were observed, while in addition, on one or two plates taken by the second method, a fourth band with maximum at about λ2650 was obtained. No evidence was found of the two continuous spectra observed by Balasse and ascribed by him to recombination,—in the one case, of the doubly ionized, in the other, of the singly ionized atom.

A discussion concerning the origin of the continuous spectrum considers the relative merits of a recombination theory, in which the atom is the ultimate source, and one according to which radiation is from excited molecules. The authors conclude that the evidence is all in favor of the latter.

INTRODUCTION

Recently Balasse[1,2,3] has enunciated the hypothesis that the appearance of a continuous spectrum in the electrodeless discharge of certain vapors is an indication of a change in the atom from a $(p+1)$th. ionized state to a pth state. In support of this view he cites the work of Esclangon[4] on cadmium, his own work on caesium and potassium[2], and, in particular, gives evidence of the existence of two continuous spectra in the case of mercury[3], one corresponding to the transition from Hg III to HgII, the other from HgII to Hg I. In essence Balasse's hypothesis is just an extension of the general idea suggested by Bohr's original theory, of ascribing continuous spectra to recombination of ions with electrons possessing varying amounts of kinetic energy. In an inverse form this has been used by Bohr to explain the continuous spectrum of sodium observed in absorption, while the continuous emission spectrum of hydrogen, has been explained by Wright[5], Crew and Hulburt[6] on the basis of recombination. More recently Mohler[7], by using a thermionic discharge tube and conditions favorable to recombination, has given evidence to show that a continuous spectrum of caesium and of potassium may be ascribed to this cause.

In the case of mercury a continuous emission spectrum has long been known, and has been observed under a variety of conditions.

Moreover, while the nature of this spectrum may not be exactly the same for all sources, it has almost the same characteristics when excited by such different means as fluorescence and the electrodeless discharge, and presumably has the same general origin in all cases. As recombination is not a probable cause in some sources, the writers are not convinced of the correctness of Balasse's hypothesis relative to the electrodeless discharge. In this paper, therefore, some further observations on the continuous spectrum of mercury are reported, together with a discussion in which it is concluded that in all cases, the hypothesis originally suggested by Van der Lingen and Wood[8,9] of ascribing the origin to diatomic or polyatomic molecules is the more probable cause.

RÉSUMÉ OF DIFFERENT METHODS OF EXCITING CONTINUOUS SPECTRUM OF MERCURY

Before describing the experimental work, a brief resumé is given of the various methods of exciting the continuous spectrum.

(1) In the fluorescent light of mercury vapor, it was first observed by Hartley[10] whose pioneer work was followed by the extended investigation of Van der Lingen and Wood[8]. When the vapor was excited by light from a zinc spark, these authors observed fluorescent light, visually evident by a green glow which was found to emit a continuous spectrum. Spectroscopic analysis showed the presence of—(1) a band extending throughout the visible with maximum intensity at 4850; (2) a less intense broad band, with maximum at 3300, (3) a narrow asymmetrical band in the neighborhood of 2356, and (4) a band with maximum about 2346.

Recently Pringsheim and Terenin[11] have made a careful examination of factors affecting the intensity of the fluorescent light.

(2) Using an electrodeless discharge as source, Kowalski[12], Robertson[13], Balasse[2] and Dejardin[14] have observed a continuous spectrum. Visual observation of Kowalski and of Robertson showed the broad band with maximum in the blue-green, while the more recent work of Balasse reports one of the two continuous spectra observed as extending from 6000 to 2300. Dejardin, working only in the far ultraviolet, records continuous from 2700 to 1850.

(3) Phillips[15], exciting mercury vapor to fluorescence with wave length 2536, showed that light continued to be emitted when the vapor streamed away from the place of excitation. The spectrum of this after-glow gave a continuous spectrum very similar to the

fluorescent spectrum. Houtermans[16], who has recently made a careful examination of the emission spectrum by a similar method records the 4850, 3300, 2537 bands together with one at 2560.

(4) Duffieux[17] states that, by rotating an evacuated sphere containing a large drop of mercury at a temperature in the neighborhood of 120° a phosphorescent light is observed which emits only a continuous spectrum. Franck and Grotrian[18] have studied the green glow obtained when drops of mercury rub the hot walls of a quartz tube and find the same general characteristics as in the Phillips after-glow method.

(5) Grotrian[19] in an important paper, showed that the green glow and a continuous spectrum could be excited by electronic bombardment of tolerably dense vapor (temperature nearly as high as 200 C). Spectroscopic observation revealed the existence of the green visible band, a band between 3400 and 2670, the spectrum ending in a third diffuse band at 2540.

(6) Child[20] observed the emission of a continuous spectrum which he considered identical with that of Van der Lingen and Wood, when a discharge is passed through an unconstricted tube, at low current density, with pressure greater than 1 mm, and temperature above 120°C.

(7) Rayleigh[21,22,23], in an exhaustive study of the nature of the continuous spectrum of long duration, (a) confirmed the results of Van der Lingen and Wood for fluorescent excitation, at the same time pointing out that the bands were in reality part of an unbroken continuous spectrum extending from red to the 2537 band; (b) observed the same spectrum in the case of an induction coil discharge through vapor continuously distilling; (c) by a careful examination of the region in the neighborhood of 2537, showed that the continuous emission spectrum ends at 2535.9, that is, about 0.6 Angstrom on the less refrangible side of 2536.5 ($1^1S_0 - 1^3P_1$).

(8) Dejardin[14] states that the quartz mercury vapor lamp "Henri George" emits a continuous spectrum identical with the fluorescent spectrum, with sudden drop in intensity in the neighborhood of 2537, although extending much weakened into the region of shorter wavelengths.

In this connection we may mention also the recent work of Dawson and Crew[24], who in the spectrum of an arc at atmospheric pressure, report the existence of bands with maxima at 4500, 3300 and 2350.

(9) Finally, in a recent note in Nature, Winans[25] has given a brief account of still another method of exciting a continuous band spectrum. Using a closed quartz tube, 15 cm long, 7 mm wide, with one external electrode joined to one side of a Tesla secondary high frequency coil, the other end of which was earthed through the primary, Winans has obtained continuous bands with maxima at 4850, 3300, 2540 and 2345.

EXPERIMENTAL

A carefully evacuated cylindrical quartz tube, 3 cm diameter, 15 cm long, with a plane polished window at one end, was used in each of the following investigations. In the first (experiments by Mr. Zinn) the tube *T*, Fig. 1, surrounded by a small cylindrical electric oven,

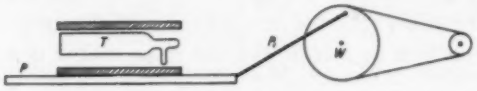

FIG. 1.

was placed on a platform *P* kept in a to and fro horizontal motion by means of the driving rod *R*, which in turn was attached to the wheel *W* rotated by a motor. In this way, by roughly focussing the end of the quartz tube on the slit of a small Hilger quartz spectrograph, the spectrum of the light emitted as a result of the rubbing of the mercury on the quartz walls could be conveniently photographed at different temperatures. Approximate temperature readings were taken by means of a micro-ammeter in a circuit including a thermocouple, one junction of which was placed against the walls of the quartz tube.

At room temperature a faint glow was visible. As the temperature rose, the intensity increased, becoming also more greenish in color until a maximum was reached, possibly in the neighborhood of 200°C. When the quartz tube became red, the glow disappeared. When the oscillations were not too rapid it was easy to follow the very bright discharge taking place between the walls of the tube and the rolling drop. Two typical spectra are given in Nos. 9 and 10, Plate II. In these it will be seen, although not as clearly in the reproduction as in the original negatives, that, in addition to low level arc lines, there is a continuous spectrum with the following three characteristic bands. (1) The broad visible band, with maximum estimated about 4600; (2) a second broad band with maximum about 3340; (3) the narrow

band ending abruptly at about 2537. (The use of a wide slit prevented a detailed examination of this band). One or two exposures were made with Schumann plates to see if the resonance spark line 1942 was present, but no trace of it was found.

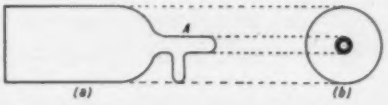

FIG. 2.

An examination of the spectra reproduced will show that the continuous spectrum is not distributed with uniform intensity over the whole slit width, but is confined to two (sometimes three or more) narrow bands running at right angles to the lines. The explanation probably lies in the fact that when the rolling drop reached the end of the tube marked *A*, in Fig. 2(a), the bright discharge took the form of a ring, somewhat as indicated in Fig. 2(b). This bright discharge to which reference has already been made, is probably nothing but a low pressure, low voltage arc resulting from the potential difference between the quartz and the mercury. Obviously the continuous spectrum is emitted, at least largely, from this region. The presence of other horizontal bands of continuous radiation is probably due to the bright flashes which occur when the drop strikes the window end of the tube.

Discussion of these results will be postponed until the details of the second investigation (experiments by Mr. MacKinnon) have been given. The object of this piece of work was to find out the most favourable conditions under which a continuous spectrum could be obtained when mercury vapor was excited by the electrodeless discharge. In particular it was desired to find out whether spark lines were emitted or not, along with the continuous bands. In the case of caesium, Balasse[1] had stated that the continuous spectrum appeared with maximum intensity when both arc and spark lines were present with comparable intensity, whereas it failed to appear if spark lines had disappeared, arc alone being present. While from the brief note of Balasse[2] regarding mercury it is difficult to find out the relative intensities of arc and spark lines when the continuous spectra is present, presumably the same condition as for caesium should hold, that is, the first continuous spectrum should be well developed when both arc and first spark lines are present. The early visual observations of one

of the writers were, therefore, extended, and a careful photographic examination was made in both the visible region and the ultraviolet.

The quartz tube, surrounded by a cylindrical tube of alundum around which 12 turns of heavy nickel wire were wrapped, was placed inside an electric oven. When high frequency currents traverse the nickel coil, one obtains an electrodeless luminous discharge whose appearance depends on the temperature. To keep the temperature as constant as possible, the electric heating was automatically controlled by means of the expansion and contraction of the air in the bulb *B*, Fig. 3, attached to a U-tube containing mercury, the rise and fall of which made and broke the circuit *C*. To assist further in maintaining constancy of temperature, the high frequency currents were used intermittently by means of a commutator on a motor shaft and a relay circuit. The mechanism should be clear from Fig. 3.

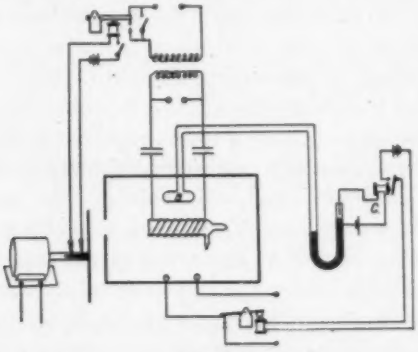

FIG. 3.

Spectrograms were taken, a few in the visible with a double prism Ladd spectrograph, the majority with a small Hilger quartz instrument, the image of one end of the quartz tube being in all cases focussed on the slit of the spectrograph. Generally speaking, the results obtained show that (a) long spark gap (of order of 1 cm) and high temperature ($200 \pm$ °C) are favourable for the development of the continuous spectrum; (b) with such conditions, exposures of several hours bring out the continuous spectrum with good intensity, together with low level arc lines, spark lines being either absent altogether or extremely feeble; (c) at a critical temperature ($96° \pm$) for a gap of about 1.2 mm both arc and first spark lines appear with comparable intensities, without any sign of continuous.

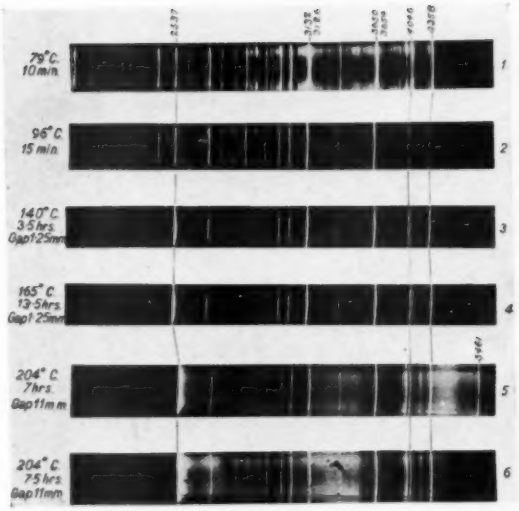

PLATE I.

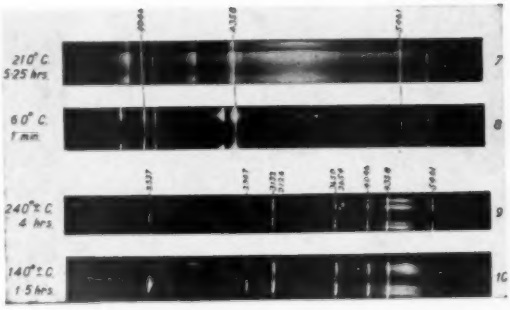

PLATE II.

In common with Dejardin[14], the authors have found no evidence of the existence of two continuous spectra corresponding to the recombination of doubly and singly ionized atoms. It may be, however, that the temperature control was not exact enough to obtain the necessary conditions, for Balasse states that a very slight change in temperature will cause the fusion of the two spectra. Unfortunately full details of Balasse's work cannot be obtained from his short notes.

The reproductions in Plate I, as well as 7, 8, Plate II illustrate the results obtained and need but little explanation. No. 1 is an example of a portion of the spectrum of the strong ring discharge obtained at low temperature, showing numerous arc and spark lines. No. 2 is taken at approximately 96°C, at which critical stage, for a gap of 1.25 mm, low level arc lines are strong as well as Hg II 2848, although this only at the edges (in the region of the stronger field). Exposure 15 minutes. Nos. 3 and 4 show the spectra at higher temperatures, with the same gap as for No. 2; No. 3 at 145°, exposure 3.5 hrs.; No. 4 at 165', exposure 13.5 hrs. Arc lines alone are now present, while in the case of the higher temperature, the naked eye can just distinguish on the plate traces of continuous.

At 145° the discharge presents a greenish glow, which, at higher temperatures, becomes more intense.

Nos. 5 and 6 are taken when the luminous discharge is on the point of being extinguished, with a spark gap of the order of 1 cm, No. 5 at 204°C, exposure 7 hrs.; No. 6 at 204°, exposure 7.5 hrs. Although No. 6 was taken with a Schumann plate, there was no sign of the resonance Hg II line 1942.

Nos. 7 and 8, Plate II are reproduced to show the contrast in the visible between the spectrum of the green glow at high temperature and that of the bright ring discharge at low temperature. Although the exposure for No. 8 is 1 min. and for No. 7, 5 1/4 hrs., it will be noticed that the arc lines in each come out with comparable intensities.

Spectra, such as Nos. 5, 6 and 7, show that the general nature of the continuous spectrum is very similar to that obtained by other means. There is the broad band in the visible with maximum about 4600, the weaker band with maximum about 3340, the narrow sometimes very intense band about 2537, and in some plates, No. 6 for example, apparently a fourth band in the neighborhood of 2650. In no plates, however, was a band at 2345 observed.

A close examination of the 2537 band, particularly in one or two

plates (No. 5 for example) showed the presence of the lines 2534.77 and 2536.52, with the continuous beginning abruptly about 0.7 Angstrom on shorter side of the resonance line—a result in good agreement with that given by Rayleigh.

We may conclude, therefore, that the continuous spectrum emitted under the conditions obtaining in the methods described in this paper is very similar to, if not identical with that observed in fluorescent vapor, in phosphorescent and in vapor subjected to electronic bombardment.

DISCUSSION

Two general theories of the origin of this spectrum have been advanced. (1) As already noted, its origin has been ascribed to recombination, in which case the atom is the ultimate source. (2) The majority of observers consider that excited molecules are responsible for its emission. According to Wood freshly distilled vapor is necessary for the formation of such molecules which are subsequently excited by the incident light. According to Franck and Grotrian excited molecules are formed as a result of a heteropolar union of an excited atom with a neutral atom.

If the first hypothesis is correct, we should expect continuous bands to be associated with the energy levels (outer orbits) into which electrons of varying kinetic energy fall, the continuous regions extending from the limits corresponding to such levels, to regions of higher frequencies. Moreover, unless all the electrons fall into the lowest level (which is extremely improbable), the continuous bands should be accompanied by the arc lines resulting from the further "drop" of electrons to lower levels. Making use of the strong arc lines present, we might then expect bands associated with 1^3S_1(λ4580), $2^3D_{1,2,3}$ (λ7800), 1^3P_1(λ2233), and (if we assume the strong infrared line 10139 present), also 2^1S_0(λ4938). If electrons fell to the 1^1P_1 level (which, however, is not the *initial* level for any line observed) λ3300 would also be a long wave-length limit of another band on this theory.

Now, while *maxima* undoubtedly coincide roughly with the limits 4580 and 3300, there is no evidence of any coincidence of either maxima or edges of bands with the other limits. As already noted, the presence of maxima at 4500, 3300 and 2350 has been observed by Dawson and Crew[24] in the spectrum of an arc at atmospheric pressure. According to these investigators, their results are in agreement with the recombination theory. On the ordinary theory, it is difficult to see how this

can be the case, although it is possible that a variation of the theory due to Wright[8] and applied with some success in the interpretation of the hydrogen continuous spectrum, may also provide a more satisfactory explanation in the case of mercury. The writers, however, can see no way of doing so.

Another objection to the recombination theory is found in the fact that the exposures of several hours necessary to bring out the continuous bands, give *lines* of only moderate intensity. Now, on the recombination theory, associated with each wave length in the continuous, there must also be the line corresponding to the further drop of the electron, except, again in the rare case when the recombining electron falls initially to the innermost level. Since only a few lines are present, and because of the big range of wave lengths included in the continuous, it follows that we might reasonably expect that by the time enough energy has been radiated to bring out the continuous spectrum with fair intensity, these few arc lines would be tremendously overexposed. Such, however, is not the case. Compare for example, the 1 min. exposure reproduced in No. 8, with the 5 hr. exposure in No. 7. In this connection mention may be made of the fact that both Wood and Rayleigh were able to obtain the same type of continuous spectrum without the presence of any arc lines.

Again, according to Balasse, with caesium vapor the continuous spectrum appears best when arc and spark lines are present with approximately equal intensities. When, however, conditions are favorable for the emission of the continuous bands by both the methods described in this paper, spark lines, if present at all, are extremely feeble. As already noted, Schumann plates showed no sign of 1942, the resonance spark line of Hg. II. While this is not direct evidence against the recombination theory, it is in conflict with those observations of Balasse used by him in support of this theory.

A further argument against the recombination theory is found in the fact that, while ionization undoubtedly exists in the electrodeless discharge, the same type of continuous spectrum has been produced when there is no ionization. In Grotrian's[19] method of excitation, for example, there were no positive ions present because the electrons never attained the velocity necessary to ionize. Moreover the continuous spectrum is not quenched by applying an electric field to the afterglow.

In the opinion of the authors, therefore, there is little doubt that the continuous spectrum is not radiated from atoms, but is in some way

connected with molecules. This view is supported by the fact that increased density, up to a certain limit is favorable for its emission. In the rolling drop method, the continuous bands are emitted largely from the discharge between the drop and the walls of the quartz tube. In the immediate neighborhood of the drop, especially at temperatures ranging from 150° to 200°C, it is not improbable to assume a high concentration of atoms. In the electrodeless discharge, the higher the temperature the greater the intensity until conditions are reached at which no discharge can be obtained.

If it is granted that the origin of the spectrum under discussion is molecular, there still remains the question of the exact nature of the excitation process or processes. Concerning this diverse views have been offered. Franck and Grotrian[18] suggest a union of a neutral with an excited atom to form an excited heteropolar molecule, the energy of which is radiated as a result of the gradual weakening of the binding. Pringsheim and Terenin[11] consider that originally unexcited molecules are subsequently excited and then put into a metastable state by collision. Houtermans[26], who has given experimental evidence that the 2537 and 4850 bands are of shorter duration than the 3300 and one observed at 2650, concludes that there are two excitation conditions of the molecule, one related to the 2^3P_1 state of the atom, the other to the 2^3P_0 atomic state. As the results presented in this paper throw no further light on the excitation process resulting in the continuous emission, a detailed discussion is out of place. It is the writers' view, however, that the work of Houtermans indicates the probable path which future experimental work should follow, and that is, in the separate examination of each band. The recent work of Winans[25] points to the same conclusion.

It has been suggested to the authors that a careful examination of the ordinary (that is, not structureless) band spectra in Fig. 7, Plate II, would reveal the presence of impurities whose effect on the origin of the truly continuous bands might be important. As the object of this paper is to present evidence that the continuous spectrum is not due to recombination, and as the work cannot be immediately continued, this question is left for the subject of a possible future investigation.

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KINGSTON, CANADA,
JUNE, 1928.

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[22] Rayleigh, Proc. Roy. Soc. (A), *111*, p. 456; 1926.
[23] Rayleigh, Proc. Roy. Soc. (A), *113*, p. 620; 1927.
[24] Dawson and Crew, Bull. Amer. Phys. Soc., *3*, p. 3; 1928.
[25] Winans, Nature, *863*, June 2, 1928.
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OPTICAL CONDITIONS FOR DIRECT SCANNING IN TELEVISION

By Frank Gray and Herbert E. Ives

By direct scanning in television we mean that method of scanning by which an image of the object is formed by a lens upon the scanning device. In terms of television apparatus most common with present day experimenters, this means forming an image upon a disc provided with a spiral of holes, as illustrated in Fig. 1. This method of scanning is the first to occur to everyone, and figures in the earliest discussions of the subject. The obstacle to its use has been that the amount of light which can be picked up by a photoelectric cell or other light sensitive

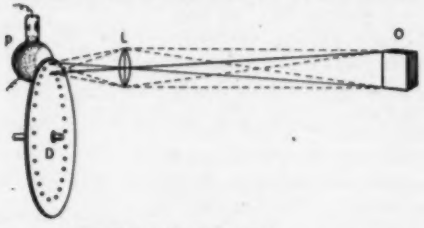

Fig. 1. *Direct Television Scanning*
O—Object whose image is to be transmitted.
L—Image-forming lens.
D—Disc provided with spiral of holes.
P—Photo-electric cell.

device placed behind lens and disc holes, is excessively small, and has indeed heretofore been considered too small to give usable photoelectric currents. For that reason, we have had recourse in the system of television developed in the Bell Telephone Laboratories[1] to the method of *beam scanning*[2] in which a beam of very intense light is projected through the scanning disc on to the subject, and the reflected light is picked up by large area photoelectric cells. By this means, the effective illumination of the subject may be thousands of times greater than the apparent or mean illumination, and much greater than is obtainable by any ordinary flood light illumination.

We have, however, recently been able to achieve television of objects illuminated by natural daylight by using the comparatively simple

[1] Symposium on Television, Summer Convention A.I.E.E. June 1927, and Bell System Technical Journal, p. 551; Oct. 1927.

[2] Gray, J.O.S.A. & R.S.I., p. 177; March 1928.

method of direct scanning. In order to do this, we have made use of a certain consequence of a study of the optical conditions peculiar to television. These studies have brought out in brief that the light gathering power of a lens and television scanning disc may be increased *by increasing the physical dimensions of the whole scanning system.* It is consequently only necessary to use scanning discs of large diameter, and image-forming lenses of corresponding large size to get any desired amount of light. There are, of course, practical limitations to the size that such apparatus may be built and used, but fortunately concurrent advances in the sensitiveness of photoelectric cells have made it possible to achieve satisfactory results without pushing the apparatus beyond practical dimensions.

The optical feature in television of which we take advantage resolves itself in its last analysis to the fact that the image is divided into a finite number of elements, and that these elements, namely the holes in the scanning disc, increase in size and light gathering power as the whole apparatus is enlarged. In terms of representative television apparatus, consider an image of a distant object formed on the television scanning disc by a lens. Let the image be one inch square, and let it be divided into 2500 elements, then each element is 1/2500 of a square inch in area. If now, we form a similar image of ten square inches area but divided into the same number of elements, the image transmitted will be exactly the same as to quality (detail) as before. Each element at the scanning end can, however, now receive ten times as much light. For, in forming the larger similar image, we either decrease the distance between lens and object, so that the lens collects substantially ten times the light it did before, or we use a longer focus lens, which, if of the same ratio of area to focal length as the original lens, likewise collects and delivers to the image ten times the light. In each case the *illumination* of the image is the same as with the original smaller image. Each hole in the disc now receives the same light per unit area as originally, but being ten times larger in area actually gets ten times as much light; that is, we have outstanding a gain exactly in proportion to the increased area of the holes.

We may express these facts in formula form as follows: Let C be the photoelectric current produced by the light reaching the photoelectric cell, A the area of a hole in the scanning disc, and I the illumination of the hole. Then we have obviously:

$$C = KAI \tag{1}$$

where K is a proportionality factor depending on the sensitiveness of the photoelectric cell. In order to introduce the dimensions of the lens as well as the disc, we must express the illumination (I) as a function of lens characteristics. We shall consider only the case, which is the one of practical interest, where the distance from the lens to the object is many times that from lens to disc, so that the lens-disc distance changes very little as the working distance is varied. Under these conditions the solid angle, Φ, subtended by the lens from the disc may be treated as a constant. If now we form the image of a uniformly bright element before the lens, on to the disc, the illumination of this image is constant, irrespective of the distance of the element (with the limits above set), and our formula becomes (the image of the element being assumed always larger than a disc hole):

$$C = K'A\Phi \tag{2}$$

where K' is another proportionality factor. This formula shows at once that to increase the photoelectric current generated from each aperture we may either increase the size of the disc [we assume that the number of holes in the disc, that is of picture elements, remains the same], or increase the solid angle ["aperture" in photographic parlance] of the image-forming lens, or increase both.

Considering first the aperture of the image-forming lens, our limitation to increase here is the preservation of adequate definition and illumination over the size of field in which we are interested. Practically at the present time our limit is in photographic lenses of aperture approximately $F/2$. The practical limitations to size of disc are set by questions of mechanical strength and of the value of space at the transmitting station. It is quite possible to rotate a disc at sufficient speed for television purposes (15 to 20 times per second) as large as 10 ft. in diameter. Comparing such a disc with discs of approximately 1 ft. in diameter which have been used in our previous television experiments, we have here an advantage of 100 fold, which is a significant factor in solving the problem.

Actually in our experimental work it has not been necessary to go to such large discs in order to obtain usable signals from sunlit objects. We have been aided in our work by the recent development in our laboratory of photoelectric cells of greatly increased sensitiveness, description of which will be given at another time. With these cells, we have been able to transmit television images from 50 hole discs

(2500 elements) using a scanning disc of 3 ft. diameter and a lens system of aperture $F/2.5$. The sending apparatus as set up on the roof of the laboratories is shown in Fig. 2. The receiving apparatus is as before, a small disc in front of a Neon lamp with a large flat cathode.

The discussion of the problem as given has been entirely centered around the question of getting light to the photoelectric cell; no variables connected with image formation or image size appear in the formula (2). This is because from the point of view here used we look on the matter of what image shall be formed as being entirely a matter of choice of

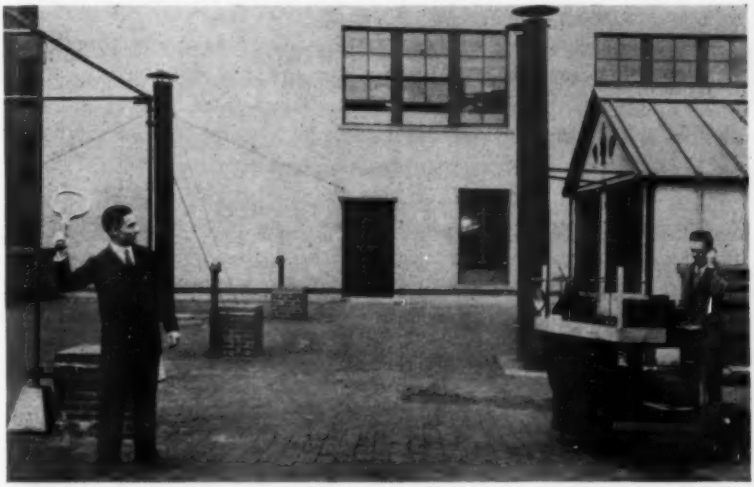

FIG. 2. *Apparatus for direct television scanning as set up on roof of Bell Telephone Laboratories.*

working distance and focal length of lens, subject to the practical limitations of available lenses just as it is in practical photography. Thus in the set-up shown in Fig. 2, a full length human figure is scanned if the subject stands about 30 feet from the lens. We cannot cover a full length human figure at a much shorter distance because the kind of $F/2.5$ lens we use if of shorter focal length will not cover the whole scanning field on the disc. On the other hand if the figure we wish to scan is more distant from us, we can, just as the photographer does, either arrange to move closer to it, or to use a longer focus lens of the same ratio of diameter to focal length. By using the latter expedient

it would be possible, with several different lenses, to handle both close-ups and wide angle views of an athletic event with one scanning disc.

The analysis of the relationship between lens aperture and disc size as above given is presented in its simplest form. It is complicated by considerations of the defining power of the lens in relation to its size and to the size of field it covers. Thus if the area of adequate definition of a lens should be approximately in reciprocal relation to its aperture (Φ), a reduction in the aperture of the lens could be offset by a corresponding increase in the size of the disc holes with a proportionate decrease in working distance or increase in focal length of the lens in order to secure an image of larger size to cover the new scanning field.[3] If then an increase in disc size were for any reason more practicable than a further improvement in lens aperture, the optimum condition might be met in that way. However, as above indicated, it has been possible with commercially available photographic lenses to attain practical television signals with discs of reasonable size.

It has been assumed thus far that the number of image elements is fixed in advance. This is usually the case, since the cost of the electrical transmission, as expressed in width of the frequency band necessary, forces the use of the lowest number of image elements which will adequately carry the picture required. If, however, a different number of image elements is decided on than that for which a satisfactory scanning system has been worked out, the changes in dimensions necessary to preserve the same photoelectric currents may be derived from the considerations already discussed.

Suppose for instance it is decided to build a system with double the number of image elements. This means using a scanning disc with $\sqrt{2}$ times the number of holes. Simple geometry shows that, to preserve the same sized holes in the new disc, this must be twice the *diameter* of the original disc, and that the *area* of the field will be twice that originally scanned. The new lens must have the same ratio of diameter to focal length as the old and, if it were to just adequately cover an image of the new size, but with the same number of elements as the old, would have to be twice the area of the first one. Here, however, we meet again the consideration of the dependence of covering power on aperture. Our image elements are now more numerous and hence

[3] Another way of looking at this, which is not obvious from although not in conflict with formula (2), is that, as the size of the disc holes is increased the lens must be moved toward the object or increased in diameter, so as to subtend a proportionately larger solid angle *from the object.*

smaller, so that if the original type of lens was just sufficient, it will not be satisfactory under the new conditions. For instance, an $F/2$ lens might just cover a rectangular image with definition satisfactory for dividing into 2500 elements, but not well enough for 5000 elements. If then it becomes necessary to drop back to an $F/2.8$ lens to get adequate definition (according to the relation assumed previously), the whole apparatus would have to be increased in size again; a disc would have to be used larger in area by the ratio of the areas of the aperture $F/2$ and $F/2.8$, that is 2 times, or 1.4 the diameter. On the assumptions made therefore, doubling the number of image elements demands nearly three times the diameter of disc. The true figure must, however, lie between three and two because there is some gain in the defining power of a lens with increasing area; the image of a point formed by a 12 inch lens is less than twice the diameter of the image formed by a 6 inch lens of the same photographic aperture.

One final point may be touched upon which is more a matter of psychological optics than physical optics. It has been rather commonly held that in order to produce satisfactory television images of full length figures or groups of figures it would be necessary to use a very much finer grained image than those that have been used thus far for the transmission of the human face. It has been interesting to find that with our 50 line, that is 2500 element images, which are just sufficient for the transmission of clearly recognizable faces, the rendering of full length figures or even of two or three figures simultaneously is surprisingly satisfactory. The reason for this appears to be largely psychological. It appears that when full length figures are observed, one's expectation of rendering of detail is automatically reduced; that is, where with a face filling the whole field, one expects to see such details as nostrils and eyelids clearly defined, where we have full length figures we are satisfied if we see head, hands and feet clearly differentiated from the other details of corresponding large size. In other words, the criterion of resolving power appears to be a certain fraction of the size of the field irrespective of the kind of objects seen. The effect is very much as though the observer were looking through a window. If someone on the other side of the window holds his face up close enough to fill the whole opening we expect to see fine detail in the face. If, however, the person walks away from the window until we see him at full length, we no longer expect to distinguish fine details of the face. In consequence of this apparent automatic compensation, once the

television image has been made of fine enough grain so that the individual scanning lines are not visible and any familiar object can be satisfactorily rendered, other objects of whatever size are still rendered with a considerable degree of satisfaction.

BELL TELEPHONE LABORATORIES,
NEW YORK, N. Y.
JULY 12, 1928.

Practical Television. By E. T. Larner. Pp. xv+175. D. Van Nostrand Company, Inc., New York, 1928.

This presents a popular account of the development and present state of television. As is mentioned in the foreword by John L. Baird, a complete understanding of television requires a knowledge of all branches of physics and of the physiology and psychology of vision as well. To present so broad a field in a popular form adapted for the average reader in 175 pages is a difficult task and the author has not always been particularly fortunate in his choice of material or method of presentation. Parts of the book appear to be too elementary to appeal to the man reasonably well grounded in the fundamentals of science and entirely too much condensed to give a complete picture to the average reader, thus failing to meet the demands of either class. However, the book contains much that will be found interesting. The American reader will profit greatly by reading the detailed description of the Baird system of television, which has been given but little publicity in our popular scientific periodicals, and will probably be surprised at the same time to find so little space devoted to a description of the work of the research staff of the American Telephone and Telegraph Company in this country.

I. C. GARDNER

INSTRUMENT SECTION

A CAMERA FOR MAKING PARALLAX PANORAMAGRAMS

By Herbert E. Ives

The name "Parallax Stereogram" was used by Frederic E. Ives to describe the stereoscopic transparency pictures invented by him,[1] in which the two component pictures were present as alternating fine strips, each series of strips visible to a single eye through a grating standing at an appropriate distance in front of the composite picture. The term "Parallax Panoramagram," I use to describe an analogous type of transparency picture, due to C. W. Kanolt,[2] in which in place of two pictures in strip form behind each clear grating space, there is an infinite series of strips, or a *panorama*. As the transparency, with its attached grating, is viewed from different angles, by a single eye, the picture seen through the grating spaces changes continuously, in the same manner that the originally photographed scene would change.

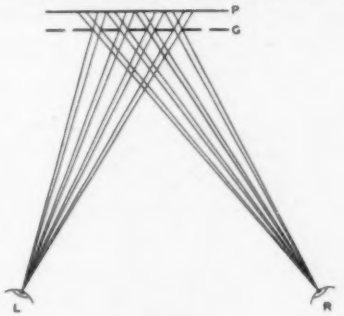

Fig. 1

Viewed by both eyes a "panoramagram" presents stereoscopic relief, and, unlike the parallax stereogram, which must be held at a definite distance and angle, the panoramagram shows a relief picture at all distances, and at any angle. The purpose of this note is to describe a form of camera for making these pictures; and to record some observations on the results obtained with it.

The problems presented in the design of a camera for this purpose are most easily understood if the characteristics of the final positive picture are described. Consider first the parallax stereogram, as shown in diagrammatic section in Fig. 1. Here R and L represent the two

[1] U. S. Patent 725,567; 1903.

[2] U. S. Patent 1,260,682; 1918.
See also, G. Bessière, Comptes Rendus, *182*, p. 208; 1926.

eyes; G, the opaque line grating, in which the clear spaces are approximately half the width of the transparent; P, the positive picture, some distance behind G, and consisting of alternating strips of the right and left eye elements of the stereoscopic pair. A camera for taking the original negative can, quite obviously, be constructed by reversing the light paths, using two lenses, proper care being taken to invert the images, as for instance by the use of roof prisms. Consider next the panoramagram, shown in section in Fig. 2. Here, as before, R and L represent the two eyes, P the positive and G the grating, which is now, however, ruled with a high ratio of opaque to clear space, in order that a small motion of the eyes will expose a new series of infinitesimal strips. At R' and L' are shown two new positions of the eyes, at which they each see new views, again forming a stereoscopic pair. If the clear spaces in the grating are narrow enough, and the transparency picture has been properly made in the first place, it is obvious that the eyes may be placed in any position in front of the grating (within limits to be discussed later) and a stereoscopic picture will be seen.

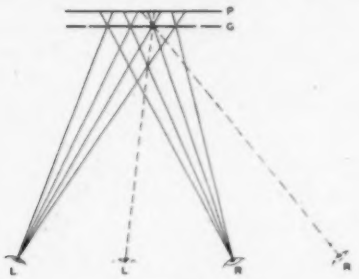

FIG. 2

Where the parallax stereogram is made with a pair of lenses the panoramagram is to be made with an infinite number of lenses, or, what amounts to the same thing, *a single lens continuously moved laterally during the exposure.* There are, however, several optical and photographic problems to be gotten around before the apparently simple operation of moving a lens across in front of a grating and plate will yield the kind of negative required. These may be listed as follows: (a) the inversion of the image by the photographic lens, (b) the partial inversion of the image by the photographic printing process, (c) the problem of positioning the image with respect to the plane of the grating, i.e., making an object appear in front of or behind the frame

of the picture, (d) the operation of focussing the apparatus after it has been arranged to take care of the other requirements.

Without entering into a discussion of several alternative means by which the several requirements might be met,[3] we may examine at once the final design of camera as worked out, in which all the problems listed above are solved in a comparatively simple way. This is shown in Fig. 3 in a simplified diagrammatic form. The essential feature is that the object (O), the lens (L) and the sensitive plate and grating (S and G), the latter rigidly clamped together (with a thin separator) as a unit in a special plate holder, are kept in line with each other as the lens and plate holder are moved laterally. The requisite motion is produced by having the lens and plate holder move along a track

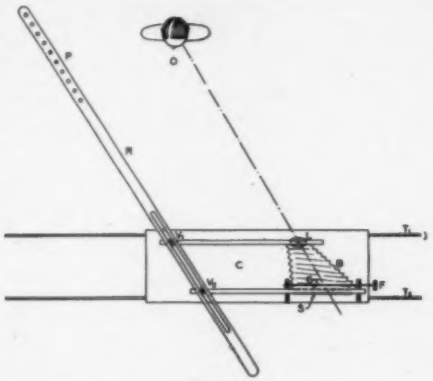

FIG. 3.

(T_1T_2) with their relative positions governed by a rod *pivoted at the object which is to appear in the plane of the final picture*. For obvious reasons of convenience the rod R is pivoted not at the object, but to one side (at P) and the pins (V_1 and V_2), which, sliding in a groove in the rod R, govern the lateral motion of the lens and plate holder, are carried out to the side of the camera body. The camera back, in which

[3] Kanolt and Bessière describe forms of cameras (loc. cit.). Kanolt moves the sensitive plate with respect to the grating, with which it is in contact, while the whole camera pivots around the object. Bessière moves the lens, which is provided with a reversing prism, from the the normal to one edge of the plate, across the plate, moving the whole camera as well to increase its range. Bessière's arrangement is fundamentally bettered if a roof prism is used instead of a reversing prism since the lens can then be moved equally far to either side of the normal and the picture is obtained unreversed. Neither of the cameras is in my opinion as elegant or flexible as the one here described.

the plate holder is inserted, is mounted rigidly as to lateral motion on the carriage C, but is free to move forward and back by the rack and pinion F for focussing purposes, while the lens board is free to move only laterally on the carriage C. A bellows B connects the lens board and camera back.

The operation of the camera is as follows: With the lens at the middle of the track the pivot P is set opposite the portion of the object which is to be in the plane of the final picture, for instance the eyes, if a portrait is to be made. The camera is focused in this position by the rack and pinion F. The carriage C is then moved to one end of the track; the plate holder, containing grating, separator and plate is inserted, the slide drawn, and the carriage set in motion by means of a motor and cog wheel drive (not shown in the figure). As the carriage travels along, the lens moves from one side of the normal to the plate to the other, always keeping on the line between object and plate. When the carriage has reached the other end of the track the lens is capped, the plate removed and developed.

Positive prints made from the negatives produced by this camera are right side up and right way around when viewed through a grating like that used in taking. When the same separator is used between grating and positive as between grating and sensitive plate, and the viewing distance is the distance between taking lens and plate, the picture appears in correct relief at all angles of viewing.

Parallax panoramagrams as made in this way are very striking objects; they have, however, one characteristic limitation due to the finite size of the grating lines. In the experiments with this camera, which made pictures 5×7 inches, the grating had 50 lines to the inch and the ratio of opaque to clear spaces was 10:1. With this size of clear grating lines the definition of objects much in front of or behind the picture plane was poor due to the inevitable overlapping of many images. Much finer clear spaces would have improved this (assuming spreading by diffraction would not have offset the expected finer definition) but at the expense of light, which is already at a premium with the grating used. While this defect is not serious in portraits if the plane of the eyes and mouth is well defined, it becomes so if such objects as machinery or furniture are photographed.

While theoretically the angle through which a panoramagram can be observed can be made as large as desired, it is limited practically in the camera here described by the angular field which the lens L can

cover. In the experiments made with the camera the lens used covered approximately 90°. The thickness of the separator between plate and grating was accordingly made approximately half the distance between grating lines. With this arrangement the whole surface of the plate is exposed; the relief picture is visible through 90°, but beyond 45° to the normal the picture starts to repeat itself.

This type of picture will be recognized by students of stereoscopy as intermediate in character between the parallax stereogram and the complete relief picture suggested by Lippmann, consisting of many minute lenses, each forming its own complete image of the scene before the plate. In this latter kind of picture (which would be excessively difficult to realize practically) objects preserve their proper relief and proportion for all positions of the observer. In the panoramagram, while the picture is visible at all distances and angles, only objects in the picture plane preserve their shapes rigidly correct, since the angles subtended in the vertical direction as the viewing distance is changed are to the picture plane and not to the apparent position of the object. This, while a theoretical defect, is not nearly as serious as the loss of definition away from the picture plane, above noted.

I take pleasure in acknowledging my indebtedness to Mr. Carl Percy, for whom this camera was constructed, for leave to describe it at this time.

NEW YORK, N. Y.
SEPTEMBER 6, 1928

A SENSITIVE VACUUM TUBE VOLTMETER

By Charles Bayne Aiken

ABSTRACT

There is described a new type of vacuum tube voltmeter which makes use of the heterodyne principle. The use of this meter is restricted to the measurements of steady, single frequency voltages in the audio and lower radio frequency range.

The meter has a linear characteristic and is extremely sensitive, the model described having a sensitivity of four scale divisions per millivolt. A sensitivity three times as large as this has been obtained by employing a different type of galvanometer and it is probable that by using the best type of galvanometer available this could be increased to the order of one division per microvolt.

Measurements may be made of weak signals which are accompanied by a relatively strong noise background.

It is shown that when the proper values are chosen the calibration is little affected by small variations in the voltages of the various batteries which are used. An exception is the filament voltage of the rectifier tube which must be held constant.

The measurement of extremely small alternating voltages of frequencies in the audible range presents many difficulties and the sensitivities of the majority of instruments available for such measurements are in no way comparable with those of direct current instruments. The vibration galvanometer is one of the most sensitive devices for the measurement of small alternating currents but its sensitivity decreases rapidly with increasing frequency and such instruments are not commonly used on frequencies above 500 or 1000 cycles. It is a resonant instrument which must be carefully tuned to the frequency of the current and its resistance is usually too low to allow it to be satisfactorily used as a voltmeter.

The Duddell thermo-galvanometer is one of the most sensitive instruments for ac measurements but its cost is high and its sensitivity is by no means equal to that of high grade dc instruments.

Thermionic meters which record the variation in space current due to the heating effect of a current in the filament can be made sensitive to small changes in a relatively large current but are not suitable for the measurement of small currents. Nor can this drawback be remedied by superposing the small current to be measured on a large current of different frequency, or on a direct current. For in such a case the R.M.S. value of the heating current is equal to the square root of the sum of the squares of the components and if one current is small compared with the other its effect will be inappreciable.

The sensitivity of the ordinary vacuum tube voltmeter is very poor. Preliminary amplification is often used in conjunction with such meters but when this process is carried far trouble is likely to develop from feed back, and the device becomes extremely sensitive to mechanical and electrical shock. Also it is impossible to measure a signal which is accompanied by a noise background of the same order of intensity.

Finally, it is to be noted that with the exception of the vibration galvanometer, sensitive ac instruments have a non-linear calibration curve, at least near the zero end of the scale.

The present meter is restricted in its application to the measurement of steady, single frequencies, but lacks many of the above mentioned drawbacks. It has a linear characteristic, is extremely sensitive and can be used to measure a weak signal which is accompanied by a noise background several times as loud.

In the rectification of small oscillations the maximum efficiency of rectification is obtained when operation takes place on the portion of the characteristic of the rectifier having the greatest curvature. The magnitude of the rectified current is proportional to the second derivative of the characteristic of the rectifier and its external circuit taken together and to the square of the impressed voltage. On the other hand, if we impress a small oscillation on the rectifier together with a large oscillation of nearly the same frequency, we get a rectified current which has a component of beat frequency and the amplitude of this component can be made equal to the product of the impressed small voltage and the first derivative of the characteristic of the rectifier system. The beat current can be made independent of the amplitude of the large signal over a limited range of that signal. This occurs when using a heterodyne system adjusted for maximum sensitivity.

It can be readily shown that the sum of two sine waves of nearly equal frequency can be represented by a single sine wave, the amplitude and phase angle of which are slow functions of time. Furthermore, if the difference in the frequencies is small and the amplitude of one component is small relative to that of the other then the variation in the phase angle may be neglected in calculating the beat frequency currents and the amplitude of the impressed oscillation is closely given by $e=E_1-E_2 \cos pt$, in which E_2 is small compared with E_1 and $p/2\pi$ is the beat frequency. In Fig. 1 there is shown a characteristic of the usual type on which is impressed a sine voltage of large amplitude. The result is complete rectification and when the amplitude of the oscillation

is such that the peak lies on the straight portion of the characteristic it is qualitatively evident that if the amplitude is changed by a small amount the change in the rectified current will be directly proportional. Now if the amplitude changes periodically due to heterodyning then the beat frequency current will be directly proportional to the amplitude of the small incoming voltage, (assumed to be constant), as long

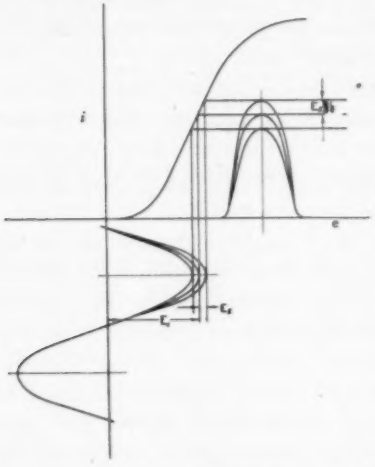

FIG. 1. *Example of adjustment of heterodyne for maximum response.*

as the peak of the voltage wave is on the straight part of the characteristic. The beat frequency current will be $E_2 \cos pt.\ \partial i/\partial e$, the derivative being that of the characteristic curve of the whole circuit. Thus if the device is a two element vacuum tube the characteristic must be that of the tube and external circuit together. In a three element tube the derivative involved will be $\partial i_p/\partial e_g$, or the mutual conductance for the given plate circuit impedance.

For small values of E_2 the product $E_2\ \partial i/\partial e$ is much larger than $E_2^2\ \partial^2 i/\partial e^2$ which is the important term in the rectification of a single frequency, and hence the sensitivity of heterodyne detection is much greater.

In the case of detection with grid leak and condenser, impressing a signal on the grid results in a decrease in the plate current, instead of an increase, but the same general argument applies with modifications which are obvious.

If the beat frequency is made as low or lower than the natural frequency of oscillation of a dc galvenometer then the variations in the rectified current can be read on a sensitive instrument of this type.[1]

It might be supposed that great difficulty would be experienced in obtaining consistent readings with a slowly oscillating dc meter. This, however, is not the case. It is entirely feasible to make the beat frequency lower than the natural frequency of many types of meters and when this is done the readings are easily made and may be readily reproduced. With some meters it is even possible to adjust the beats to resonance with the meter and still obtain consistent readings. The amplitude of the oscillations is, of course, a maximum for the resonant condition.

DESCRIPTION AND OPERATION OF THE METER

The circuit diagram of one of the meters which has been built is shown in Fig. 2. The Hartley oscillator furnishes a local voltage the

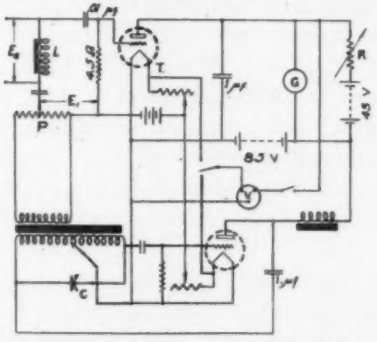

FIG. 2. *Circuit of heterodyne voltmeter.*

magnitude of which is controlled by the potentiometer P of 10,000 ohms total resistance. The choke coil L of approximately 250 henries may or may not be used, depending on the character of the circuit which is connected to the input. The local voltage E_1 and the input voltage E_2 are in series and are impressed on the grid of the rectifier tube T. Grid circuit rectification is employed as this gives a sensitivity much higher than that obtainable by plate circuit rectification.

[1] This feature is utilized by F. Dacos in an oscillographic device which he describes in a paper in: Bull. de L'Assoc. des Ingenieurs Elec. de L'Inst. Electrotechnique Montefiore, *5*, p. 1, 7th Series, Jan. 1927. His arrangement depends for its operation on special properties of the four electrode vacuum tube and differs from the present system in several important points. Dacos gives no quantitative data on the sensitivity of his device.

The 1 mf condenser which is shunted across the plate circuit of tube *T* serves to bypass the signal frequency components of the plate current while the beat frequency current must pass through the galvanometer *G*. The impedance of the condenser to this current is extremely high since the beat frequency is adjusted to less than one cycle per second. A balancing battery and resistance are used in conjunction with the galvanometer so that when no signal is coming in the needle can be adjusted to the middle of the scale. A high voltage balancing battery is used and hence a high resistance is required at *R* with the result that a large fraction of the beat current will flow through the galvanometer rather than through *R*.

In most of the measurements which have been made with this instrument one or more stages of amplification have been employed in front of the input. When this is done the choke coil *L* is included in the plate circuit of the last amplifying tube. If it is desired to listen to the incoming signal, *L* may be replaced by a pair of high resistance phones. This will reduce the amplification somewhat but this small reduction may often be allowed. If this is not the case the grid circuit of another tube may be connected across *L* and the phones inserted in the plate circuit. By this means the incoming signal may be heard and as it is almost impossible to keep the local signal out of the various circuits, beats are readily audible. In fact beats may sometimes be heard when the incoming signal is too weak to hear directly. The local frequency can be adjusted by means of the condenser *C* until the beat frequency becomes low enough to actuate the plate circuit galvanometer. Final adjustment to the correct frequency is made by means of a vernier condenser in parallel to *C*. By observing the amplitude of the oscillations of the needle as the frequency is decreased it is easy to make sure that the frequency is sufficiently low to allow the meter to follow readily and when this is the case the readings are made without difficulty.

A small Leeds & Northrup portable, pointer type, galvanometer was used in many of the tests. The rating of this instrument is .5 microamperes per mm. It has a rated period of three seconds and is highly damped. It was found that resonance effects were very small and that beats could range in period from two seconds up without changing the amplitude appreciably. With the apparatus in proper working order a suitable beat frequency is quickly obtained and a few swings of the needle are sufficient to give the reading with fair accuracy.

All of the parts of the apparatus, except the batteries, were inclosed in a metal case which made a fairly effective shield. However it was found that if strong stray fields of the frequency under measurement were present additional shielding was necessary.

A calibration curve of the instrument is shown in Fig. 3. It is quite linear and very small oscillations may be read with reasonable accuracy. The sensitivity is seen to be .25 mv/mm. This is with type 199 tubes

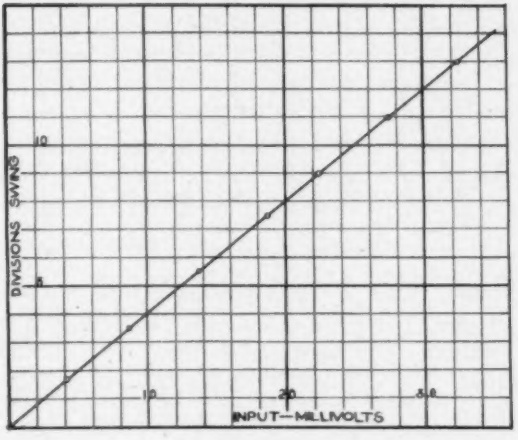

FIG. 3. *Voltmeter calibration curve.*

in both oscillator and rectifier. A rectifier tube having a higher mutual conductance should give a proportionally higher sensitivity. The ordinary type of vacuum tube voltmeter employing 199 tubes cannot be used on signals of less than about .2 volts. Hence for measuring voltages in the lower end of the useful range the heterodyne voltmeter is of the order of 1,000 times more sensitive than the ordinary type of meter.

In Fig. 4 is shown a curve of response as a function of local voltage, all other parameters being held constant. This is the curve marked $E_b = 85$ volts. It is to be noted that for a local signal of between 3.0 and 3.5 volts the response, for a fixed input voltage, is practically independent of the local voltage. This is an important advantage since it makes small variations in the oscillator output unimportant.

The second curve of Fig. 4 shows the effect of varying the plate voltage of the rectifier tube, the input and local voltages being held con-

stant, the latter at the value for optimum response. In the vicinity of 85 volts the response is not effected by small variations in the plate voltage.

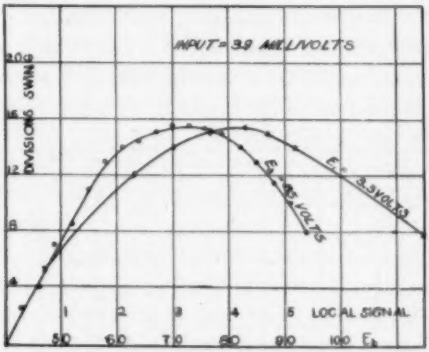

FIG. 4. o *Effect of variation in local signal.*
x *Effect of variation in voltmeter tube plate voltage.*

The calibration curve of Fig. 3 was taken with best values of local and plate voltages as determined from the data of Fig. 4, thus insuring maximum sensitivity and minimum dependence of the calibration on these quantities. A grid leak of 4.5 megohms was used as it had been

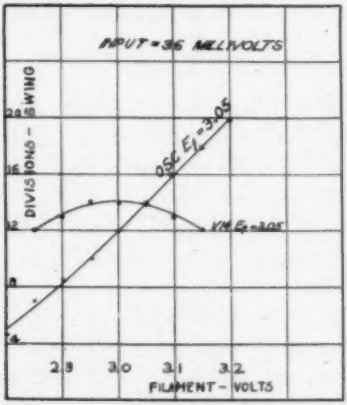

FIG. 5. o *Effect of variation in oscillator tube filament voltage.*
x *Effect of variation in voltmeter tube filament voltage.*

found that the response was somewhat less for lower values of the leak resistance.

In Fig. 5 are shown two curves which show the effect of changes in

the filament voltage of the oscillator and of the rectifier. It is to be noted that changes in the oscillator voltage are relatively less important. This is to be expected since the effect of changing the filament voltage of this tube is to change the amplitude of the local signal and as this is adjusted for the optimum condition it follows that any variation from the value 3.05 volts, which had been chosen for the operating value, should result in a decrease in the response and the curve should have a flat maximum similar to that of the local voltage curve of Fig. 3.

On the other hand the response increases approximately linearly with the rectifier filament voltage and hence it is important that this quantity be frequently checked while measurements are being made.

Since the intensity of the local oscillations changes when C is varied, the optimum voltage must be determined for a number of frequencies in the range to be covered and from this data there may be plotted a curve of settings of the potentiometer against frequency.

Difficulties Encountered in the Operation of the Meter

One of the most troublesome phenomena encountered in the operation of the meter is a tendency of the local oscillator to lock into step with the incoming signal. If this locking tendency is completely effective the motion of the needle ceases or becomes entirely erratic. However, the trouble may result in a regular but non-sinusoidal motion of the galvanometer needle. This makes readings unreliable and prevents adjustment to resonance with the natural frequency of the galvanometer. If the constants of the oscillator are such as to result in strong oscillations this locking tendency is not serious even with signals large enought to give full scale deflection of the galvanometer. If however, the oscillator is so adjusted as to be on the verge of cessation of oscillations then the tendency to lock is greater.

Another trouble frequently met with is a drifting of the zero position of the galvanometer due to small variations in the voltages of the various batteries in the circuit. By using large capacity B batteries and well charged storage cells for the filaments this trouble can be eliminated. It is also extremely important that the variable resistances be of the wire wound type and that the sliding contacts and switches be in proper working order. Molded variable resistances were found to be responsible for great unsteadiness of the galvanometer needle.

If there is a noise background present signals that are strong enough to give a good deflection may be entirely inaudible in the head telephones. Under such circumstances difficulty may be experienced in

adjusting the local frequency to a value sufficiently near that of the incoming signal to allow the galvanometer to respond. In many cases it is possible to arrange an auxilary listening circuit which derives power directly from the source of the signal and by feeding a small amount of power into this circuit from the local oscillator the beats may be heard. If this cannot be done it is necessary to slowly and continuously vary the local frequency until the galvanometer begins to oscillate.

When a signal is being measured which, although weak, is derived from a nearby strong source, it may easily happen that there are spurious pickups in the voltmeter circuit and these are likely to cause false readings. If, however, the pickup is in the oscillator circuit the effect may be to cause the oscillator to lock in step with the signal source. Proper shielding will usually overcome such difficulties.

USE AS A MICRO-VOLTMETER

A large number of measurements have been made on voltages ranging down to a few tenths of a microvolt. There was used in conjunction with the heterodyne voltmeter an audio frequency amplifier with an

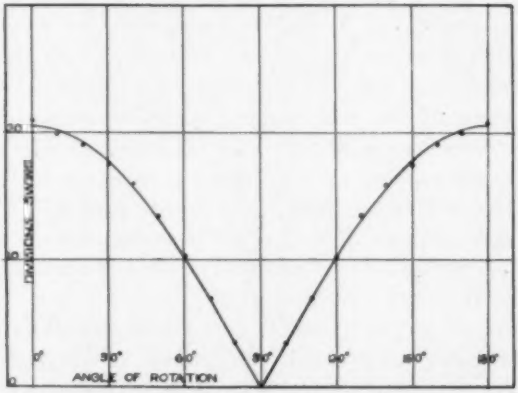

FIG. 6. *Response to voltage induced in a small exploring coil.*

overall amplification of almost exactly 1,000. The grid of the first tube was maintained at a negative bias of three volts so that the input impedance was extremely high. The output circuit of the amplifier included the coil L of Fig. 2. The amplification was held constant by frequently checking the battery voltages.

As an example of the operation of this system there is shown in Fig. 6 a curve of response plotted against the angular position of a small

pickup coil which was connected to the input of the amplifier and rotated in the stray field of a 1,000 cycle oscillator. The smooth curve is a cosine curve drawn to fit the observed readings which are indicated by circles. The maximum voltage induced in the coil was just over five microvolts. The coil also picked up a considerable signal from the 60 cycle power mains. The maximum value of this signal was judged to be two or three times as intense as that of the 1,000~ signal but had not the slightest effect on the galvanometer.

If this measurement were to be made with the ordinary type of vacuum tube voltmeter using a type 199 tube it would be necessary to use a preliminary amplification of 1,000,000 instead of 1,000 in order to get an equally satisfactorily response for the lower voltage portions of the curve. This would introduce the numerous troubles which always accompany the high amplification of audio frequencies. Furthermore such a system would have been so affected by the 60 cycle signal that readings of the 1,000 signal would have been impossible.

Most of the present work has been done in the frequency range between 700 and 1400 cycles, but there should be no difficulty involved in covering the entire audio frequency range if a sufficiently flexible oscillator were used. This system of measurement should also be applicable to crystal controlled signals in the lower range of radio frequencies. It would require less amplification than other systems of measurement and would be insensitive to static and to interfering signals.

EXTENSION OF THE SYSTEM

It is not necessary that the rectifying part of this system be a vacuum tube. Experiments with a set up similar to that which has been described above but employing a copper oxide rectifier in place of the detector tube have been quite successful.

Considerable sensitivity might be obtainable by using a heterodyne system in conjunction with thermionic space current meters. The effective heating current can be made to vary at a slow rate and it is possible that the temperature of a small filament might follow the current fluctuations. We have here the input current serving to vary the amplitude of the main heating current instead of the square of the input current being added to the square of the heating current. In the latter case the effect is negligible but in the former the sensitivity should be good as such meters respond readily to small changes in large currents.

Tests with a sensitive vacuum thermocouple used in conjunction with a heterodyne input showed that the couple was much too sluggish in its temperature changes to be used in this way.

The galvanometer used in the above experiments is one that is not particularly sensitive and it might be expected that greatly increased response might be obtained by using a more sensitive instrument. Of course if this is done it will be necessary to take increased precautions against drifting of the zero point due to changes in the battery voltages. Furthermore, high sensitivity galvanometers usually have long natural periods and would require too fine an adjustment of the beat frequency, which adjustment might be hard to maintain for a long enough time to get several complete swings of the galvanometer. However a considerable improvement over the present galvanometer should be feasible. Some work was done with a small Weston galvanometer that was rated at twice the sensitivity of the Leeds & Northrup instrument, the period being the same. The damping was not nearly so high and resonance effects were quite noticeable. However, it was possible to maintain the beat frequency in resonance with the meter frequency with the result that instead of getting twice the response with this instrument, swings of three times the amplitude of those registered by the less sensitive instrument were obtained. The Cambridge Instrument Company manufacturers a reflecting galvanometer having a period of 3.5 seconds and giving a deflection of 800 mm per micro ampere at one meter scale distance. It is possible that by using this meter with the heterodyne system voltages of the order of one microvolt could be measured without preliminary amplification.

The oscillator used in the voltmeter described above was of the Hartley type. Experiments were also carried on with what is commonly known as the Western Electric oscillator. With this setup the tendency to lock into step with the incoming signal was very much less, but the sensitivity was considerably less than with the Hartley circuit. It seems that the incoming signal effects the intensity of the oscillations of the local oscillator to a small extent and that this shows itself in increasing the overall sensitivity of the device. The effect on the Hartley circuit is greater than on the more stable Western Electric circuit.

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LIQUID JETS FALLING THROUGH AN ELECTRIC FIELD

By A. E. Parker

Not long ago a preliminary suggestion[1] was made concerning the behavior of a liquid jet when falling through a non-uniform electric field. This present note covers a more detailed study of this subject, made by means of spark photography described in the paper referred to above.

As is well known, a falling jet appears to be attracted as well as separated into a spray by an electric field. Is this scattering due to the electric field breaking the jet into drops, or, are the drops the natural result of gravity which are then separated by the electric field? Can one have a jet repelled by an electric field? What is the distribution of the electric charges on the drops as they fall in an electric field? These were some of the questions which arose regarding these jets.

Figs. 6 and 7 in the former paper show a falling jet of water, without and with an electric field respectively. To the unaided eye the drops in Fig. 6 look like a continuous stream, but when separated as in Fig. 7 they appear as a spray as explained in Fig. 8 of that same paper.

Figs. 1 and 2 in this paper show two different water jets in the presence of electric fields. Fig. 1 had its field produced by a hard rubber rod rubbed with cat's fur. The rod was about 35 cm long and 1 cm in diameter. The field in Fig. 2 was maintained by a hard, rubber rod about 30 cm in length and 3 cm in diameter. In both cases the jets are attracted by the rods but do not break into drops and sprays until they are well out of the maximum field of the electrified rod. The jet in Fig. 2 is just getting ready to break in the lower right hand corner of the figure, 6 to 8 cm below the rod. This would indicate that the electric field of the rubber rod attracts the water whether in a continuous jet or in drops, and that the spray does not arise, in general, until the drops are formed by gravity and then separated by the electric field.

In both of these photographs the jets are neutral. The attraction both for the jets and for the drops are due to the induced charges. In Fig. 3 is shown the distribution of the charges on the jet and drops. In all cases the smaller drops are deflected more than the larger ones, hence the spray form. Fig. 4 shows a jet of water which has broken

[1] Woodbridge and Parker, J.O.S.A. and R.S.I., *16*, p. 125; 1928.

just as it leaves the outlet of a burette with a fairly large opening. Fig. 5 shows a falling jet of mercury. The same conditions seem to exist here as in the jets of water. In all of the photographs a plumb-line has been suspended for showing the deviations of the jets.

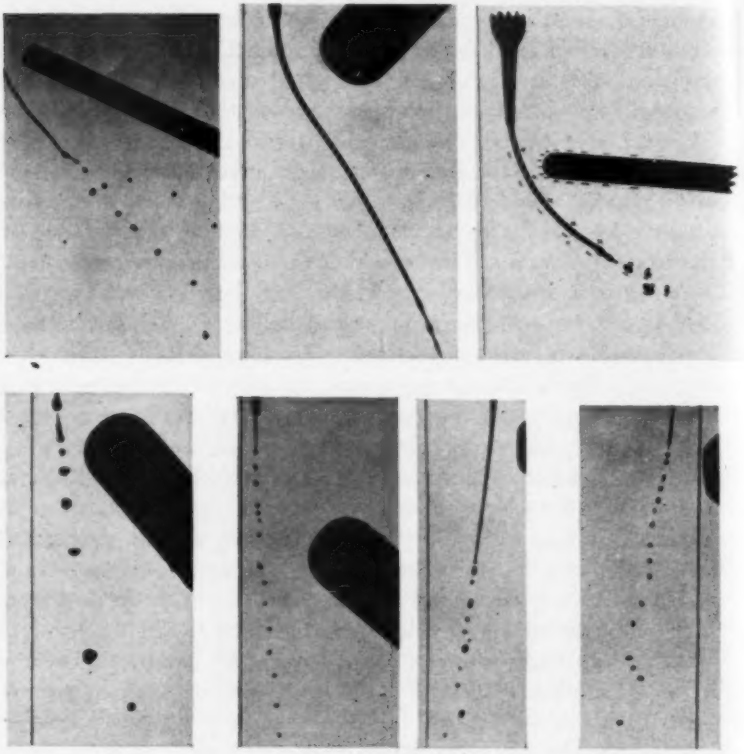

FIG. 1. *Water jet deflected by an electric field.*
FIG. 2. *Water jet deflected but unbroken.*
FIG. 3. *Distribution of electric charges on rod, jet and drops.*
FIG. 4. *Falling jet with large drops of water.*
FIG. 5. *Falling jet of mercury.*
FIG. 6. *Jet of water repelled.*
FIG. 7. *Jet of mercury repelled.*

It was found that, if an electric field was produced by a spherical electrode connected to one pole of a static machine, it would repel a liquid jet connected to the same pole of the electric machine. A re-

pelled jet of water is shown in Fig. 6 while Fig. 7 shows a similar condition for mercury. In these two cases the repelling force acts between the like charges put on the sphere and the jets. Furthermore, there is a spray as in the cases of the attracted jets.

The author is indebted to Mr. Philip Johnson who helped in making the photographs and also to Professor S. R. Williams who suggested the problem.

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TRANSMISSION OF ULTRAVIOLET RADIATIONS BY QUARTZ PRISM MONOCHROMATORS

By William T. Anderson, Jr., Hugh D. Fraser, and Lester F. Bird

The many varied applications of ultraviolet radiations by the physician, the photochemist, the biologist, and the experimenter in general have stimulated the use of quartz prism monochromators. In spite of the increasing popularity of this type of optical instrument, very little appears to be known about its transmission characteristics.

The authors have been using two large quartz prism monochromators of their own construction. The design of both was based on the plan of a simple spectrograph. The light which entered through a slit of adjustable width, passed through a collimator lens, was spectrallized by the prism, and could be brought to focus by means of a lens on another adjustable slit located at some distance behind the instrument itself. Any desired wave length of light could be transmitted through this rear slit by rotating the prism table in the proper manner. The wavelength of the transmitted light could be determined by photography employing a quartz spectrograph with a calibrated wave-length scale, or in the case of the ultraviolet and a light source with a familiar spectrum by the examination of the fluorescence spectrum produced on an uranium glass plate held against the rear slit and between the slit and the focussing lens of the monochromator. The arrangement of the prism and the rear slit was such that when the infra red portion of the spectrum was in focus on the slit, the light on the prism was at an incidence of about 60°, whereas when the short ultraviolet was on the slit, incidence on the prism was about 30°. One of these instruments had a fused quartz optical system, 100 mm objectives, prism 100 x 100 x 100 mm. The other was of crystal quartz, 75 mm objectives, Cornu prism 60 x 60 x 80 mm.

In the course of determining the spectral energy distribution of different light sources, it was necessary to know the relative transmission of the crystal quartz monochromator, and at the same time it was of interest to learn the transmission efficiency. It was considered advisable to determine the transmission directly by measurement rather than to rely on calculations of reflection at the quartz-air surfaces. The procedure involved (1) a determination of the relative ultraviolet transmission with respect to wave length, (2) a measurement of the spectral

energy distribution of the light source, (3) a determination of the total ultraviolet energy which enters and is transmitted by the monochromator, (4) by consideration of (2) and (3) an estimation of entering ultraviolet at each wave length and transmission at each wave length when quartz mercury arc is employed immediately before the front slit.

1. RELATIVE ULTRAVIOLET TRANSMISSION WITH RESPECT TO WAVE LENGTH

The determination of the ratio of energy of monochromatic light entering the front slit of the crystal monochromator to the energy transmitted through the exit slit for a number of monochromatic bands of ultraviolet radiation gave a measure of the relative ultraviolet transmission of the monochromator with respect to wave length.

Fig. 1 shows the arrangement of the apparatus.

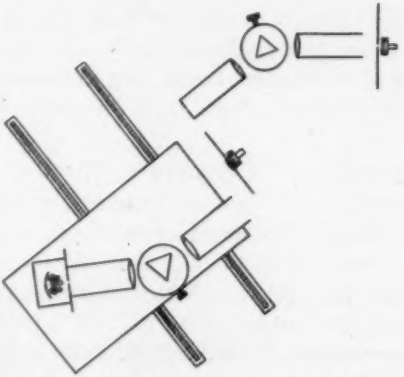

FIG. 1. *Horizontal Plan of optical system.*

The monochromatic light source consisted of the fused quartz prism monochromator illuminated by a vertically mounted mercury anode type quartz mercury arc lamp. The entire system was mounted on a car and track. The rear slit of the fused monochromator was not on the car, being supported in a fixed position along side the front slit of the crystal monochromator. The front and rear slits of both instruments were exactly the same in construction and dimensions, and the openings were maintained at 44 x 1.2 mm during all these measurements. The preceding arrangement permitted a monochromatic band of light to be transferred from the rear slit of the fused quartz monochromator to the front slit of the crystal instrument by the motion of the car a pre-

determined distance. The transfer was accomplished without a change in focus or alteration in the quantity of light energy passing through the slits, i.e., the energy measured by a thermopile mounted directly behind the slits was in each instance the same. The light transmitted by the crystal monochromator was brought to focus on its rear slit, and the energy measured by a thermopile placed directly behind.

Two bismuth-silver thermopiles were used in these experiments. They were calibrated against a standard incandescent bulb supplied by the U. S. Bureau of Standards. 1 mm deflection of a d'Arsonval galvanometer at a scale distance of 2 meters was found to correspond to 0.124 and 0.128 erg/sec/mm^2. One of these piles was employed directly behind the rear slit of the fused quartz monochromator to indicate the light energy which was entering the crystal instrument, and the other was used behind the rear slit of the crystal monochromator to measure the transmitted light energy. No lenses were used in front of the thermopiles. Since these measurements were purely relative, the areas of light on the piles were of no consequence as long as they did not vary with wave length. The constancy of the areas was demonstrated by photography.

The quartz mercury arc was operated at 78 volts 3.5 amperes. The purity of the monochromatic light produced by the fused quartz monochromator was established by spectrograms taken behind the rear slit, and was further evidenced by the fact that passage of the monochromatic light through the crystal monochromator did not result in further spectrallization, which would have occurred had the light not been pure. In the measurement of wave lengths 2800, 2650, and 2537, a plate of window glass, which does not transmit these wave lengths, when inserted between the rear slit of the fused quartz monochromator and the pile prevented deflection of the galvanometer from the zero position. This indicates freedom from stray infrared radiations. Other stray radiations were eliminated by performing the experiment in a dark room.

The experimental procedure was to focus a monochromatic band produced by the fused quartz instrument on the rear slit. The area of light at the thermopile was recorded on light sensitive paper, and found to be 45 x 5 = 225 mm^2 in each instance. This light area was divided into sections in such a manner that the pile which had an area of only 30 mm^2 could measure all the energy in each section. The sum of the deflections for all the areas represented the total energy in the light

area. This procedure eliminated errors caused by uneven distribution of light energy in the area, or losses which would have occurred if lenses had been used. The car was then moved along its track to the position where the monochromatic band entered the crystal quartz monochrmator with the energy which had just been measured. The transmitted energy was measured on the pile mounted behind its rear slit, the area of light in this instance having been found to be $45 \times 1.2 = 54$ mm². The ratio between the entering and transmitted energy are a measure of the transmission at that wave length.

The results obtained are given in Table 1, the relative transmission being referred to the blue band at 4360 A.U. as unity.

Table 1. *Relative ultraviolet transmission with respect to wave length of a crystal quartz prism monochromator.*

Wave length Angstrom	Galv. defl. in mm thru front slit (L)	Galv. defl. in mm thru exit slit (M)	% Trans. monochr. light (100M/L)	Relative trans. referred to 4360 as unity
4360	294	38	13.9	1.00
4045	181	27	14.9	1.07
3660	477	78	16.3	1.17
3130	267	50	18.7	1.35
2800	24	5.5	22.0	1.59
2650	45	11	24.4	1.75
2537	21	6	28.6	2.06

It should be noted that this procedure determines *only* the relative transmission. The actual transmission obtained when a lamp is placed immediately before the front slit of the monochromator is quite different. When the lamp is used, the lamp is the light source, the radiation being emitted in all directions in general agreement with the inversed square law. However, in the above measurements, the light source was the image of the front slit of the fused quartz monochromator, the direction and intensity of radiation being controlled by the lens system of the fused quartz monochromator. Consequently the proportions of light entering the front slit of the crystal monochromator which fall on the prism in the two instances are not the same, and the transmissions given in Table 1 must be multiplied by a constant to obtain values applicable to the condition in which a light source is employed directly against the slit.

2. MEASUREMENT OF SPECTRAL ENERGY DISTRIBUTION OF QUARTZ MERCURY ARC AND TRANSMISSION OF CORNING PURPLE COREX GLASS

A measurement of transmission of the monochromator when the light source is placed immediately before the slit and without intervening lenses necessitates the use of filters of known transmission and knowledge of the spectral energy distribution of the light source. A most convenient filter is Corning purple corex glass which transmits the ultraviolet of the quartz mercury arc, and excludes other visible light and practically all infrared. The specimen of glass used in these experiments had been aged under ultraviolet radiation and consequently showed a lower transmission than would have been found with a new piece.

The distribution of the arc and the transmission of the glass were determined by placing the arc immediately before the front slit of the crystal monochromator, and measuring with a lens and thermopile placed behind the exit slit the energy in each of the more important bands. The continuous spectrum and the lesser bands were neglected, which procedure introduced an error of a possible 5% in the energy measurements. This omission does not appreciably affect the final results on the monochromator transmission. The distribution was corrected for losses in the monochromator by employing the relative transmission values obtained from Table 1.

Table 2. *Spectral energy distribution of quartz mercury arc (Hanovia) and transmission of Corning purple corex (aged)*
(Arc voltage 78 D.C., 3.5 amps., arc length 55 mm)

Wave length Angstrom	Measured Galv. def. in mm (a)	Relative monochro. trans. fac. (b)	Corrected distr. mm defl. (a/b)	% distr. Hg arc	Measured trans. Corex (c)	Corrected trans Corex (c/b)	% trans. Corex
4045	134	1.07	125	11.9	8	7.5	6
3660	405	1.15	352	33.7	186	162	46
3340	22	1.24	18	1.7	12	9.6	52
3130	272	1.35	201	19.1	128	94	47
3025	121	1.40	86	8.2	54	38	45
2967	62	1.43	43	4.1	28	19	44
2900	22	1.47	15	1.4	8	5.4	35
2800	35	1.59	22	2.1	10	6.2	29
2750	18	1.62	11	1.0	3.5	2.1	20
2700	22	1.68	13	1.2	3.5	2.0	15
2650	132	1.75	75	7.2	16	9.1	12
2537	143	2.06	69	6.6	3	1.4	2
2480	33	2.40	14	1.3	.5	0.2	1
	1420		1044			356.6	

3. DETERMINATION OF THE TOTAL ULTRAVIOLET ENERGY WHICH ENTERS AND IS TRANSMITTED BY THE MONOCHROMATOR

The ratio of the total ultraviolet entering the front slit of the monochromator to that passing through the rear slit is a measure of the transmission of the monochromator.

The measurement of the total ultraviolet entering the front slit of the monochromator when the lamp is placed immediately before the slit necessitates the elimination of the visible and infrared, and a diminution of the intensity of the ultraviolet by a known amount in order that the measuring thermopile will record only ultraviolet and that the intensity of the radiation will be sufficiently reduced to enable the galvanometer deflection to be confined to the scale.

The purple corex glass was employed to filter out the visible and infrared radiations, and a plate of window glass served to reduce the intensity of the ultraviolet. The transmissions of both these glasses had been determined for the ultraviolet, visible, and infrared. At a pile distance of 40 inches from the arc, a deflection of 18 mm was obtained through the two glasses, 39 mm for the corex alone, and 707 mm when no filters were between the lamp and the pile. The two glasses together transmitted 2.5% of the total radiant energy from the lamp. The corex and window glass together transmitted no measurable infrared from the lamp even when the glasses and pile were within 5 cm of the lamp. This was demonstrated by inserting between the glasses and the pile a plate of red signal glass which does not transmit the violet and ultraviolet, but transmits the infrared to a high degree. When this was done, zero deflection was obtained, indicating that the quantity of infrared transmitted by the corex and window glasses was negligible.

The lamp was placed before the slit of the monochromator and the corex, window glass, quartz lens and thermopile immediately behind. The area of light falling on the pile was $69 \times 2 = 138$ mm^2. This area was divided into sections and a measurement made with the pile in each section. Consideration of the areas of the sections and of the pile indicated what the total deflection of the galvanometer would have been had it been possible to have all the light on the pile at one time. The same lens and pile were employed for the measurements of the light transmitted through the monochromator so that no correction had to be made for losses at the lens.

Employing the above procedure, a total deflection of 2000 mm was obtained immediately behind the front slit of the monochromator. If

the window glass had not been used in conjunction with the corex, i.e., if the corex had been used alone, the deflection would have been:

$$\frac{18}{39}=\frac{2000}{x};\quad x=4,333 \text{ mm deflection.}$$

which represents the total ultraviolet and violet radiations transmitted through the corex glass.

From Table 2, it follows that the ultraviolet radiations which would have fallen on the pile if the corex glass and window glass were removed was:

$$\frac{1044}{356.6}\times 4,333=12,700 \text{ mm deflection.}$$

This latter value represents the total ultraviolet energy of all wavelengths that entered the front slit of the monochromator.

The total ultraviolet transmitted through the rear slit of the monochromator, using the same lens and pile as above, are given in Table 2(a). It follows that the total of the entering ultraviolet transmitted was:

$$\frac{1420}{12,700}=0.111, \text{ or } 11.1\%$$

4. ESTIMATION OF THE ENTERING ULTRAVIOLET AT EACH WAVE LENGTH AND THE TRANSMISSION AT EACH WAVE LENGTH WHEN A QUARTZ MERCURY ARC IS EMPLOYED IMMEDIATELY BEFORE THE FRONT SLIT OF THE MONOCHROMATOR

TABLE 3. *Ultraviolet transmission efficiency of crystal quartz prism monochromator.*

Wave length Angstrom	Measured Galv. in mm thru monochromator (a)	Calc. Galv. defl. in mm of entering (d) light	% Trans. of entering ultraviolet (100a/d)
4045	134	1511	8.8
3660	405	4267	9.4
3340	22	216	10.2
3130	272	2438	11.2
3025	121	1041	11.6
2967	62	520	11.9
2900	22	178	12.3
2800	35	266	13.1
2750	18	127	14.1
2700	22	152	14.4
2650	132	901	14.6
2537	143	838	17.0
2480	33	165	20.0

The measurements of the total ultraviolet energy entering the front slit of the monochromator and of the spectral energy distribution of the quartz mercury arc permit a reasonably accurate estimation of the light energy of each wave length of entering ultraviolet. These values are incorporated under column (d) Table 3. The transmitted ultraviolet measured under the same conditions, and for each wave length, are given under column (a) Tables 2 & 3. A comparison of the two gives a measure of the efficiency of the quartz prism monochromator when the light source is placed immediately before the front slit.

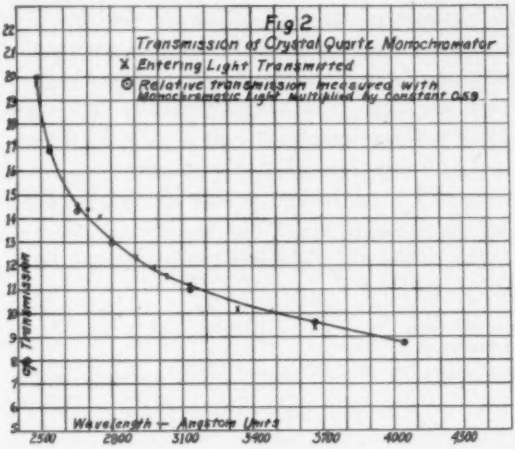

Fig. 2 shows the transmission in the ultraviolet under the above conditions, and indicates the agreement with the results obtained using monochromatic light when the latter are multiplied by the proper constant (0.59).

CONCLUSIONS

The design of this monochromator favors the transmission of the shorter wave lengths, due undoubtedly to fact that when the short ultraviolet is on the rear slit, the light on the prism is more nearly at perpendicular incidence. Since the portion of the spectrum falling on the rear slit is determined by the position of rotation of the prism, and since the angle of incidence on the prism increases rapidly as the visible and infrared portions of the spectrum are moved on the slit, it is not surprising that there should be such a marked decrease in transmission with increasing wave length.

In spite of what appears to be inefficient transmission, it should be noted that it is possible with this monochromator, using a commercial quartz mercury arc as normally operated, to obtain monochromatic-radiations of high purity and with energy content of 5×10^3 erg/sec at wave length 3660 Angstroms, and 1.8×10^3 erg/sec at 2537 Angstroms.

SUMMARY

1. The relative ultraviolet transmission of a large crystal quartz Cornu prism monochromator with respect to wave length has been determined, employing monochromatic radiation and measuring the entering and transmitted energy. 2. The quantities of entering and transmitted ultraviolet energy from the full lamp were determined, and by a consideration of the measured spectral energy distribution of the quartz mercury arc, the actual transmission at each wave length was calculated. 3. Excellent agreement was obtained between the relative and calculated transmission when the former was multiplied by a constant to correct for lens action. 4. The monochromator transmitted about 11% of the entering ultraviolet radiations. 5. A filter method by means of which the total ultraviolet energy from a light source may be determined is outlined.

RESEARCH LABORATORY,
HANOVIA CHEMICAL & MFG. CO.,
NEWARK, N. J. AUG. 16, 1928.

THE USE OF STANDARDIZED H. & D. CURVES IN SENSITOMETRY

By O. E. Conklin

The writer has believed for a long time that the determination of H. & D. constants such as speed and contrast would be facilitated if one had, ready made, a standardized H. & D. curve printed on a transparency which he could fit over the curve given by his experimental data. This standardized curve would have printed on it, its gamma and numbers describing the characteristics of its underexposure region. It would also have an index for locating the position of the experimental curve and thereby determining its speed. This index should intersect the exposure axis of the experimental curve thus locating an "inertia point" from which the speed can be determined.

Of course the standardized curve would be one of a family of standardized H. & D. curves. After much blundering we arrived at such a system in this way. First, the densities of a large number of cine positive curves having the same speed and gamma were averaged after subtracting fog. The coordinates of the average curve were:

log exposure.	0.5	.10	.25	.40	.55	.70	.85	1.0	1.6
density.	.027	.063	.118.	.203	.327	.495	.700	.960	2.160

This curve had a gamma of 2.0. Doubling its densities gave another curve with a gamma of 4.0, and by multiplying its densities by other factors the series of curves shown in Fig. 1 were obtained. The gammas of these curves range from 0.5 to 4.0 in steps of 10% or less.

From the manner in which these curves are constructed it is obvious that the projections of their underexposure regions on the exposure axis have the same length. This length is a useful index of the size of the underexposure region of an H. & D. curve. We have therefore named it "size." For our original family of curves the size came out 1.1 in log exposure units. To obtain families of curves having other sizes we simply photographed the original curves in a series of reductions and enlargements having the ratios 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0. In this way we obtained a set of transparencies containing 413 standardized curves, with which we found that we could fit practically all H. & D. curves. In applying these curves, we found that one more condition is necessary for a fit. The standard H. & D. curves

must be raised or lowered more or less with respect to the exposure axis of the experimental curve. In other words the intersection of H. & D. curves with the exposure axis differ in abruptness. This is the property which Mr. Renwick[1] calls "cut." We have preferred to call it "straightness" and to define it by the ratio between the least and the greatest slope on the H. & D. curve. In other words it is the ratio between the threshold slope and gamma.

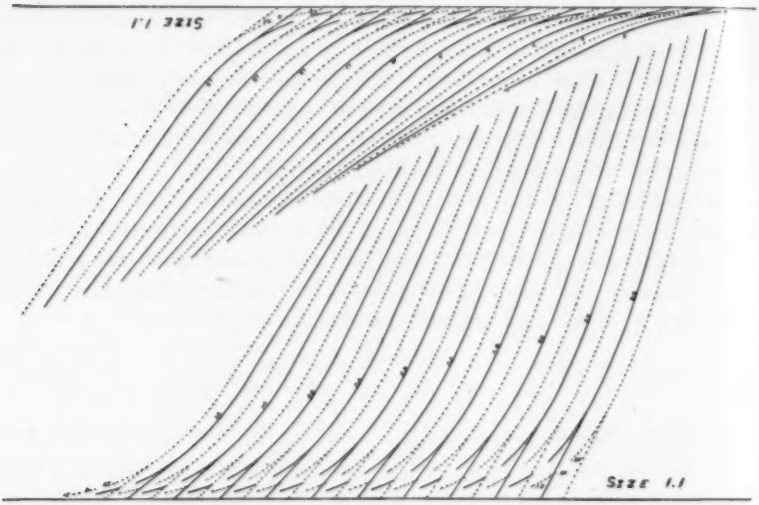

FIG. 1. *A family of standardized H.&D. curves.*

To determine straightness we have broken up the lower ends of the standardized curves into segments so as to form a direct reading scale of straightness values. The intersection of exposure axis of the experimental curve with this scale gives the straightness.

The fitting of the standardized curve to the experimental curve is made easy by first determining gamma in the usual way by drawing a line through the straight part of the experimental curve and determining its slope. This limits the number of curves to be tried and an inspection of the under-exposure region usually enables us to pick the correct curve at once. Fitting the correct curve gives the speed, size and straightness. Let us note here that the speed is determined by fitting the whole ex-

[1] Journal of the Royal Photographic Society, *53*, p. 127; 1913.

perimental curve. Usually only the points on the straight line region are used to determine speed, but here all the points contribute and consequently there is a very material increase in the precision of the speed values. In cases where it is doubtful which of two curves gives the best fit we find that the speeds given by either choice agree very closely.

We do not wish to urge the use of this system of standardized curves, but we believe that others will find it to their advantage to construct their own systems and to mark each curve with indices and figures for obtaining sensitometric constants defined according to their own ideas. By using standardized curves, figures can be obtained from H. & D. curves which would be very difficult to get in any other way. This applies particularly to the constants of the underexposure region.

The writer wishes to thank Mr. F. F. Renwick for his helpful criticism in preparing this paper.

Du Pont Pathe Film Mfg. Co.,
Parlin, N. J.

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